WHOLE BODY COORDINATION DURING TURNING WHILE WALKING IN STROKE SURVIVORS

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ABSTRACT

This body of work sought to explore kinematic impairments which may underlie falls incidences during turning following stroke and review the evidence for the effectiveness of interventions aimed at improving aspects of locomotor coordination which are key to controlling turning.

A systematic review of the literature identified insufficient homogeneity of high quality evidence to determine if task specific locomotor practice interventions are effective in improving aspects of gait coordination which are key to the controlling turning. The review highlighted a need for a better understanding of the nature of coordination deficits in functional walking tasks, such as turning, after stroke.

In order to provide a base of knowledge regarding abnormalities in the coordination of locomotor patterns during turning while walking, two experimental studies were undertaken. The studies employed analysis of full-body kinematics during turns made under pre-planned and reactive conditions as well as turns of different magnitudes and those made by participants with and without a falls history. Findings from Study 1 showed a strong trend for participants with stroke (in particular those with lesions involving the basal ganglia) to initiate pre-planned turns later than their age-match counterpart. Turns made in response to an external cue were made in a similar manner to healthy controls. Results from study 2 indicate that while participants with stroke and falls history took significantly longer to turn, all other aspects of the movement pattern were similar to healthy controls and non-fallers. Therefore, incidences of falls during turning following stroke may not be due to impaired movement patterns alone. On this basis, we suggest that rehabilitation efforts and further studies should address the interplay of impaired movement production with other factors such as attention.

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LIST OF PUBLICATIONS

Peer –reviewed journal articles derived from this body of work

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Hollands, K.L., Hollands, M.A., Zietz, D., Wing, A.M., Wright, C.C. & van Vliet, P.M. (2010). Kinematics of turning 180º during the Timed Up and Go in stroke survivors with and without falls history. Neurorehabilitation and Neural Repair: 24(4); 358-367.

Peer-reviewed internet publications derived from this body of work

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CHAPTER 1: BACKGROUND

The necessity for research into impairments of locomotor coordination during turning while walking more than six months post-stroke

The number of stroke survivors who regain independent walking ability is estimated to be as low as 18-40% (Rundek 2000; Lord 2004). Although many individuals who have had a stroke regain a basic locomotor pattern, one study has reported only 7% of patients discharged from rehabilitation are able to walk safely in the community (Hill 1997). Walking in the community and at home requires the ability to adapt gait and balance for everyday activities, including turning to change direction. The ability to turn while walking is crucial in regaining independence since 35-45% of the steps taken during everyday tasks occur while turning (Glaister 2007) . Community-dwelling, chronic stroke survivors (greater than 6 months post-stroke) are also at risk of falling during turning, (Hyndman et al. 2002; Andersson et al. 2006) and are 10 times more likely to sustain a hip fracture when they fall than age-matched individuals who have not suffered a stroke (Gustafson 2003). Research is needed to explore the mechanisms underlying falls incidences during turning.

The need for research into putative mechanisms for falls occuring while turning is particularly true in populations of community dwelling chronic stroke survivors (greater than 6 months post-stroke) in which falls incidences during turning have been identified (Hyndman et al. 2002) yet few receive rehabilitation to meet their needs beyond this time point (Health 2007). The lack of rehabilitative input in chronic stroke patients occurs despite studies (Hesse 1994; Peurala 2005; Plummer et al. 2007) providing evidence that many stroke patients can overcome persistent disability, longer than 6 months after stroke. However, support for recovery of locomotor function has not been corroborated by recent Cochrane systematic reviews which show insufficient evidence that “therapy based rehabilitation” is

effective for people more than 6 months after stroke (Aziz 2008) and equivocal evidence for the effect of task-specific locomotor training, such as treadmill training, on gait parameters (Moseley et al. 2005). Impaired gait coordination is hypothesized to result in impairments in the ability to adapt gait patterns to carry out functional tasks such as turning (Roerdink et al. 2007). Therefore, research is needed to examine evidence for the effectiveness of interventions aimed at improving impairments in locomotor coordination which may be underlying falls incidences.

The aim of this chapter is to provide the background justification for the research questions to be addressed. This will be achieved by summarising current understanding of central nervous system (CNS) control of turning while walking in healthy young adults and review evidence for stroke-related coordination deficits in walking and turning while walking. This evidence will be consolidated at the end of the chapter to set out the broad research questions to be addressed by studies in this body of work.

Control and coordination of whole body kinematics during turning in healthy participants

Coordination of axial segments during turning in healthy participants

Studies of young healthy adults have shown that for turns of 60º or less axial segments are proactively rotated to the new direction of travel in a sequential top down pattern with the eyes and head leading, followed by the trunk, pelvis and finally the feet (Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Trunk rotations in the frontal plane (roll) serve to preserve stability and aid movement of the centre of mass (CoM) towards the new travel path (Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Turns greater than 50º require more rotation from body and eye, head and trunk rotations are more synchronous when turns are

beyond the visual field (e.g. 90º or greater) and are pre-planned (McCluskey and Cullen 2007; Anastasopoulos et al. 2009).

It has previously been hypothesized that anticipatory head movements towards the new direction of travel serve to provide a stable frame of reference for the rest of the body to reorient with respect to (Hollands et al. 2001; Vallis and Patla 2004). This hypothesis is supported by the fact that the earlier the cue to turn is provided the sooner the head is seen to reorient towards the new direction of travel (Patla et al. 1999; Hollands et al. 2001). Further support for this hypothesis may be seen in the strength of cross-correlation between head angular trajectory and overall walking trajectory, and the phase lag at which the peak correlation occurs. Previous studies have found healthy adults show high cross-correlations between head rotation and overall walking direction. The peak correlation occurs at a phase lag of approximately 200ms with the head rotation anticipating walking trajectory (Courtine and Schieppati 2003a). This result indicates that the head angular trajectory anticipates and may, in some way, dictate the overall walking path. This is further exemplified by difficulties in maintaining a desired walking path when the head is oriented in a disparate direction (Vallis and Patla 2004), such as when walking straight ahead but looking into a shop window to one side.

Recent studies (Prévost et al. 2003; Sreenivasa et al. 2008) have indicated that head anticipation of the turn occurs at a constant distance from the turn point (~1.1m for turns less than 135º and ~0.9m for 180-degree turns) rather than at a constant time. For turns of 90º or greater, the head and thorax beginning to reorient to the new direction of travel at the same time. However, the head soon rotates beyond the trunk in the direction of the turn. One reason that the head rotation may exceed that of the trunk is to facilitate obtaining a view of

the new travel path for as long as possible when the new walking path is out of straight-ahead field of view (Sreenivasa et al. 2008).

Indeed it is intuitive to assume that anticipatory orientation of the head in the new direction of travel may simply subserve gaining visual information about the new travel path. This idea is initially supported by results which indicate that head and body movements during turning serve to stabilise and direct gaze in advance of turning (Imai et al. 2001). However, the head has been shown to anticipate the new direction of travel even when turning while blindfolded and no visual information can be gained (Grasso et al. 1998; Courtine and Schieppati 2003a). Since, in each of these studies, participants viewed a goal prior to performing the task blind-folded, the lack of influence of having the eyes closed could be explained by the use of a short-term spatial memory in which information about environment is updating during locomotion in a egocentric manner (Prévost et al. 2003). Nevertheless a model of locomotor control in which heading direction is dynamically guided using visual information does not explain why anticipatory head reorientation would be seen in conditions when no visual information about the new travel path can be gained.

If anticipatory orientation of the head toward the new direction of travel does not contribute to the control of turning by supporting the acquisition of visual information, how is turning controlled? A study by Hollands et al, (2004) has argued that similarities in the shape of eye-in-head trajectory and foot in space trajectory are indicative of eye-foot coordination during turning. The fact that these similarities continued to exist even when there was no visual target to turn to provides evidence that control of the body and feet trajectories during turning may not be dependent on vision but that the output of the motor systems responsible for moving the feet is heavily influenced by the motor systems responsible for generating eye and head movements (Hollands et al. 2004). More recently this hypothesis has been

elaborated to specify that the coordination of axial body segments during steering represents a robust pre-programmed postural synergy that is dependent on, and triggered by, eye and head rotation in a new travel direction (Reed-Jones et al. 2009). In other words, these authors propose that the control of the turning synergy lies in changes to vestibular and proprioceptive signals caused by movement of the eyes and head apart from any visual information that is usually acquired with gaze redirection. This hypothesis is supported by the fact that when participants were asked to maintain their gaze on a fixed point while performing a turn in a virtual reality environment, anticipatory reorientation of axial segments normally seen in a turn, were suppressed (Reed-Jones et al. 2009).

Coordination of stepping strategies during turning in healthy participants

Studies of healthy individuals have shown that turning involves altering the straight walking pattern to produce asymmetries between the left and right legs in the parameters such as step length, step width and ground reaction force (Courtine and Schieppati 2003b; Orendurff et al. 2006). The limb which is internal/ipsilateral to the turn produces a shorter step length than the limb which is external to the curve (Courtine and Schieppati 2003b) which must cover a longer radius on the circular path. As a consequence of step asymmetry the movement of the CoM towards the new direction of travel is assisted (Courtine and Schieppati 2003b). Using these stepping strategies, achieving a turn takes approximately two steps (Patla et al. 1999; Courtine and Schieppati 2003b; Paquette et al. 2008) with anticipatory reorientation of axial segments occurring in preceding two steps (Patla et al. 1999; Hollands et al. 2001; Fuller et al. 2007; Paquette et al. 2008).

Placement of the feet to conduct a turn can be critical in determining if the turning strategy executed is to be a side-step turn or a crossover turn. A side-step turn is performed if

the turn is initiated with the foot which is contralateral to the turn direction. The contralateral foot step is made wider than previous steps to drive the CoM towards the new direction of travel (Hollands et al. 2001). This strategy provides a wide base of support within which the CoM can move without approaching the limits of stability. In contrast a crossover turn is initiated when the foot ipsilateral to the turn is in contact with the ground at turn onset and the contralateral foot crosses over the ipsilateral foot to catch the CoM as it falls in the new direction of travel (Patla et al. 1999). This strategy provides a narrow base of support which may challenge stability and has been seen to be preceded by a wider step width than for preparatory steps into a side step-turn (Paquette et al. 2008).

Longer time to turn (Berg 1989; Lipsitz et al. 1991; Thigpen et al. 2000; Dite and Temple 2002), increased number of steps taken to turn (Lipsitz et al. 1991; Thigpen et al. 2000; Dite and Temple 2002) and lack of pivoting or presence of stagger when turning (Thigpen et al. 2000) have all been hypothesized to indicate turning difficulty. A lower score on the Berg Balance Scale (BBS) is given for requiring greater than four seconds to turn 360º (Berg 1989) and another study indicates longer than three seconds to turn 180º during the "timed Up and Go" (TUG) is an indicator of difficulty when turning (Thigpen et al. 2000). Suggestions for thresholds of number of steps to turn which indicate falls risk in groups of community-dwelling older adults vary from use of more than 12 steps to complete a 360º turn (Lipsitz et al. 1991) to the use of five or more steps or weight shifts to accomplish a 180º turn and an absence of pivoting during the turn as indicative of turning difficulty (Thigpen et al. 2000). The use of two or more steps to carry out a direction change has been associated with decreased balance confidence in healthy older adults (Fuller et al. 2007). It has been previously suggested (Thigpen et al. 2000) that individuals who accomplish a turn using a

multiple step strategy as opposed to a pivot strategy may do so to compensate for a lack of ability to carry out the more ballistic strategy of pivot turn.

Neural basis for control of turning coordination

Walking is thought to be composed of cyclic muscle activation and consequent kinetic and kinematic events produced by central pattern-generating networks (CPGs) located within the spinal cord (Pearson 1993; Patla 1999; Burke 2001). Generation of walking patterns simply by activating neural networks which produce rhythmic and stereotyped activation patterns is thought to have the benefit of simplifying control. However, the kinematic result of stereotyped neural activation patterns must be adaptable in order to facilitate direction change in response to environmental demands without interrupting forward progression. The fact that the way in which turning is achieved (through a stereotyped sequence of reorienting axial segments) is relatively consistent under different conditions (Grasso et al. 1998; Patla et al. 1999; Hollands et al. 2001; Courtine and Schieppati 2003a; Prévost et al. 2003; Hollands et al. 2004) is thought to indicate that turning is also achieved through a movement synergy, (i.e. a stable postural sequence activated by a single motor output), and thus reduces the complexity of controlling the turn (Prévost et al. 2003; Reed-Jones et al. 2009). Results of other studies (Courtine and Schieppati 2003a; Courtine and Schieppati 2004) indicating that muscle activation patterns of the lower limbs are only altered slightly from straight walking patterns to achieve a turn is yet further evidence that turning is controlled by using stable patterns of coordinated muscle activation and axial segment kinematics which may be generated by CPGs (Courtine and Schieppati 2004).

Evidence that goal-directed changes in the gait pattern, such as changing direction, cause modification of activity of cortical neurons in cats (for review see (Drew et al. 2004))

indicates that walking and turning movement patterns may be generated by neural networks involving the cortex and not isolated to spinal CPGs. Studies of human participants have suggested that the areas of the brain involved in controlling direction change may include both cortical *and* subcortical structures, with some specific evidence for the involvement of the basal ganglia (BG) (Mohr et al. 2003; Crenna et al. 2007) and cerebellum (Reisman et al. 2005; Reisman et al. 2007).

Recent evidence specifically indicates that the BG may play a crucial role in the control of axial segments during turning. Patients with Parkinson's disease (PD) have been shown to demonstrate simultaneous rotation of the head and trunk during turning and delayed onset of reorientation in all axial segments (Vaugoyeau et al. 2006; Crenna et al. 2007). It is hypothesized that the BG may be responsible for generating internal cues for the initiation of movement sub-components in well practiced, automatic movement sequences (such as a turning synergy) through discharge of activity in the globus pallidus (Georgiou et al. 1993). It is thought that an impairment in the production of internal cueing is one possible mechanism accounting for the slowing of movement sequence execution. This hypothesis is further supported by the fact that improvement in walking is seen in conditions when external cues are provided (Georgiou et al. 1993; Azulay et al. 2006). Recent evidence has indicated that the preferred direction of turning in healthy adults is associated with asymmetric dopamine activity such that the preferred direction of turn is unilateral to the side of less dopamine activity (Mohr et al. 2003).

Stroke survivors with a variety of cortical lesions showed changes in symmetry of steps following split-belt treadmill walking while patients with lesions to midline cerebellar structures, which project to, and receive input from, the brainstem (Morton and Bastian 2006) did not (Reisman et al. 2007). This implies that interactions between the cerebellum and

brainstem are important for symmetry of interlimb control during gait (Reisman et al. 2005; Reisman et al. 2007).

Evidence regarding the role that cortical structures may play in the control of turning is largely derived from studies contrasting stroke patients with healthy control counterparts. The ability to alter step lengths and widths during straight walking paradigms (also a critical element in turning), has been shown to be intact in stroke survivors with a variety of cortical lesions. In a study of obstacle avoidance following cortical stroke the magnitude of the alterations to step lengths and durations were greater in participants with stroke than for control participants and coincident with a much greater failure rate of crossing the obstacle (Den Otter et al. 2005). The differences between hemi-paretic and control participants in this study indicate that cortical areas may in fact be involved in controlling alterations to stepping patterns. The only studies that have described the kinematics of reactive turns in stroke survivors, reported that participants with middle cerebral artery (MCA) infarcts, reoriented axial segments to the new direction of travel simultaneously (Lamontagne et al. 2007; Lamontagne and Fung 2009), unlike healthy subjects. These results support the notion that control of sequential reorientation of axial segments when turning may be controlled by either subcortical or cortical structures both of which are supplied by the MCA.

Control and coordination of whole body kinematics during walking and turning in participants with stroke

Whole body coordination during walking following stroke

Stroke survivors demonstrate many deficits in locomotor pattern which persist despite rehabilitation interventions. Poor interlimb coordination during gait in people after stroke is reflected by impairments including asymmetries in propulsive forces between the paretic and

non-paretic limbs (Kim and Eng 2003), step lengths, widths and stance and swing phase durations (Lehmann et al. 1987; Griffin et al. 1995; Barela et al. 2000). Stroke survivors also demonstrate altered temporal and spatial coordination between the head, trunk and pelvis (Wagenaar and Beek 1992; Lamontagne et al. 2005) and impaired pelvic, knee, and ankle control during loading, mid-stance, and terminal stance; inadequate hip, knee, and ankle flexion excursion through mid-swing; inadequate knee extension, hip flexion and ankle dorsiflexion excursion in terminal swing, and abnormal timing among hip, knee, and ankle joint movements (Daly et al. 2007). All of these coordination impairments underlie overall decreased walking speed and walking endurance (Dickstein 2008). If gait coordination is impaired as a result of an underlying pathology, then functionally adaptive walking, such as the ability to change walking direction, may also be impaired (Roerdink et al. 2007).

Even after training stroke survivors find it difficult to make changes to the parameters of straight walking which are normally implemented when making a turn i.e. changing step-length and width (Plummer et al. 2007) and producing coordinated rotations of the head, trunk and pelvis (Lamontagne et al. 2005). People after stroke have also been shown to make changes in walking speed mainly through modulations of stride length whereas healthy counterparts used changes in stride frequency *and* stride length to alter speed (Bayat 2005). One study of stroke survivors performing obstacle avoidance tasks has highlighted that the amount of time available for stroke survivors to alter the gait pattern may be crucial for successful performance. Den Otter and colleagues (2005) demonstrated that decreasing the time available to modify the gait pattern to step over an obstacle resulted in significantly higher failure rates. In combination these studies suggest that stroke survivors have an impaired ability to coordinate axial body segments during turning and may need more time to implement changes to locomotor patterns in order to turn in response to changes in the

environment. Poor motor coordination and inability to adapt the straight gait pattern may therefore be underlying mechanisms causing the high prevalence of falling (Hyndman et al. 2002) during adaptive locomotor behaviours, such as turning, post-stroke.

Whole body coordination during turning following stroke

Only two studies to date (Lamontagne et al. 2007; Lamontagne and Fung 2009) have examined turning ability during walking in stroke survivors and these studies suggested that a major deficit in locomotion in the first year following stroke is the inability to sequentially reorient axial segments to the new direction of travel. Stroke survivors who were classed as more severely impaired (according to self-selected walking pace less than 0.45m/s) were found to reorient their body segments later (i.e. *after* passing the turn point compared to healthy counterparts who reoriented axial segments approximately half a second *prior* to the turn). These participants also exhibited a disrupted sequence of axial segment reorientation according to the direction of the turn such that head and gaze were reoriented first when turning to the paretic side, whereas the pelvis was reoriented first when turning to the non-paretic side. Participants who were less severely impaired demonstrated few differences in turning ability compared to control participants. Results of this study also indicate that stroke survivors may be less able to stabilise the head and gaze by making rotations in the opposite direction to medio-lateral shifts of the body mass while walking which has been seen in healthy adults (Imai et al. 2001). The authors suggest that these impairments in gaze and axial segment kinematics during turning may impact negatively on the ability of the head to be used as a stable frame of reference that the rest of the body may reorient with respect to. This highlights the need to assess and train adaptive locomotor behaviours and visuomotor control in rehabilitation of walking after stroke rehabilitation.

Work by Lamontagne et al (2009) and Lamontagne and Fung (2007) appears to indicate that control of axial segment turning synergies is impaired post-stroke, however these studies did not employ quantitative statistical comparisons between participants or participant groups and did not explore the kinematics of pre-planned turns. Further studies are needed to improve our understanding of characteristic impairments in the kinematics of turning following stroke.

Research questions

The broad base of literature describing how direction changes are implemented and controlled in healthy young adults indicates that coordination of axial segments, particularly the head with the feet, are crucial to the control of turning while walking (Hollands et al. 2001; Hollands et al. 2004; Reed-Jones et al. 2009). The fact that turning is achieved with a stereotyped sequence of axial segment reorientation for different turn magnitudes and visual conditions suggest that turning may be achieved using a "turning synergy" to simplify neural control (Hollands et al. 2001; Prévost et al. 2003; Courtine and Schieppati 2004; Reed-Jones et al. 2009). The neural networks controlling turning synergies may be both cortical and subcortical, but the BG may play a key role (Mohr et al. 2003; Crenna et al. 2007).

In contrast, very few studies have examined direction change in persons who have had a stroke. The studies (Lamontagne et al. 2007; Lamontagne and Fung 2009) which have looked at the kinematics of turning in stroke survivors are largely descriptive and only detail reactive turning ability, but suggest impaired coordination of axial segments when turning.

Although there is a general lack of knowledge concerning the control and implementation of *turning* following stroke, there is growing knowledge of characteristic coordination deficits in *straight walking* following stroke. Studies examining various straight

walking behaviours have indicated that stroke patients may have particular difficulties in altering stepping patterns, coordinating axial segments and in changing walking pattern when time allowed is restricted. These impairments may contribute to the occurrence of falls post stroke and justify the use of targeted interventions to remediate these deficits. However, no reviews have yet examined the evidence to indicate whether improvements in locomotor performance can be brought about using interventions for the restoration of deficits in motor coordination.

Therefore, the studies within this body of work aim to extend our current understanding of the nature of coordination deficits during turning while walking and review the evidence for the effectiveness of interventions aimed at improving aspects of locomotor coordination which are key to controlling turning (e.g. axial segment reorientation and stepping patterns). The following research questions will be addressed in this body of work:

- What types of interventions are used in combination with locomotor practice paradigms in order to specifically target the coordination of walking and turning? (systematic literature review)
- What is the effectiveness of task-specific locomotor training interventions in improving coordination of axial segments and lower limbs following stroke? (systematic literature review)
- What are the differences in coordination of body segments during pre-planned turns between stroke survivors and age and gender-matched control participants? (study 1)
- Do stroke survivors require more time to implement a change in walking direction than healthy counterparts? (study 1)
- Are there differences in coordination of body segments between stroke survivors with differing lesion locations? (study 1)

- Are there differences in turning kinematics between stroke survivors who have a falls history compared to those who do not? (study 2)
- How do kinematics of turning a relatively small turn (e.g. 45 degrees – study 1) compare to that of a large turn (180 degrees – study 2) for stroke survivors?

CHAPTER 2:
INTERVENTIONS FOR IMPROVING COORDINATION OF AXIAL SEGMENTS AND LOWER LIMBS DURING WALKING FOLLOWING STROKE: SYSTEMATIC REVIEW

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The need for a review of evidence for types and effectiveness of locomotor practice interventions on locomotor coordination greater than six months post-stroke

Recent Cochrane systematic reviews show insufficient evidence that "therapy based rehabilitation" is effective for people more than 6 months after stroke (Aziz 2008) and equivocal evidence for the effect of task-specific locomotor training, such as treadmill training, on gait parameters (Moseley et al. 2005). Impaired gait coordination is hypothesized to also result in impairments in the ability to adapt gait patterns to carry out functional tasks such as turning (Roerdink et al. 2007). Therefore, research is needed to examine evidence for the effectiveness of interventions aimed at improving aspects of locomotor coordination which are key to controlling turning (e.g. axial segment reorientation and stepping patterns) and which may be underlying the high incidences of falling while walking and turning in chronic stroke patients (Hyndman et al. 2002).

Background justification for the use of locomotor practice interventions to target impairments in locomotor coordination

Impaired gait coordination as a result of stroke may also result in impairments in functionally adaptive walking, such as the ability to alter walking direction (Roerdink et al. 2007). This connection is evident from the fact that reduced intersegmental coordination has been correlated with poor motor recovery following stroke (Kautz and Brown 1998) and that stroke patients have been shown to have an altered ability to adjust gait to achieve changes in speed (Bayat 2005) or in direction of walking (Lamontagne et al. 2007; Lamontagne and Fung 2009). In particular, people after stroke were shown to make changes in walking speed mainly through modulations of stride length whereas healthy counterparts used changes in stride frequency *and* stride length to alter speed (Bayat 2005). Similarly, stroke survivors were reported to have altered sequence of axial segment reorientation compared to healthy counterparts when turning a corner (Lamontagne et al. 2007; Lamontagne and Fung 2009).

In order to restore efficient, independent functional walking ability, the basic gait pattern must be flexible enough to allow modifications to coordination between moving body parts in order to accommodate variations in task requirements and circumstances, such as variation in walking speed (Olney et al. 1998; Barela et al. 2000) and changes of direction to follow paths and avoid obstacles or oncoming pedestrians (Courtine and Schieppati 2003a). Achieving direction changes requires modification of intra-and intersegmental coordination of the straight gait pattern without loss of stability. Poor intersegmental coordination may be a causal mechanism underlying the high prevalence of falling (Hyndman et al. 2002) during turning while walking post-stroke. Reduced motor coordination has indeed been correlated with poorer motor recovery (Kautz and Brown 1998). Therefore, rehabilitation targeted at

coordination of axial and lower limb segments would appear to be a mechanistic way of achieving rehabilitation aims for walking post-stroke.

Improving gait coordination and restoring the ability to adapt gait patterns according to environmental and task demands are increasingly being recognized in physical therapist practice as important components of improving locomotor performance (Roerdink et al. 2007). The repertoire of treatment methods aimed at improving locomotor performance is large and includes, but is not limited to, strength and endurance training exercises, motor imagery, functional electrical stimulation (FES), biofeedback and task specific locomotor training (Dickstein 2008). Many of these therapies are aimed at the rehabilitation of overall function rather than at remediation of specific impairments or components of the gait cycle (Dickstein 2008). However, task specific locomotor practice, such as repetition of over-ground (OG) walking or treadmill training (TT) is aimed at rehabilitation of gait impairments. Locomotor practice is thought to improve gait coordination by stimulating reorganization in the central nervous system (CNS) and thereby improve lower-limb motor control and gait patterning (Patterson et al. 2008b). Locomotor practice, either on treadmill or OG, allows repetitive practice of complete gait cycles, consistent with basic principles of motor learning that emphasize a synthesis of perception-cognition-action experiences leading to relatively permanent changes in the performance of skilled behaviours (Harris-Love et al. 2001). Importantly, this hypothesis indicates that the alteration of the gait pattern is due not just to the mechanical effects of moving the legs but also to the responsiveness of the neuromotor system (Patterson et al. 2008b). Walking practice is often complemented by augmenting stepping patterns with the use of additional interventions such as body weight support (BWS). The aim of these adjunct interventions is to further augment the normative sensorimotor

experience of walking imposed by practice and stimulate neuroplasticity with the hope that this will correlate with changes in motor control (Harris-Love et al. 2001).

One review (Moseley et al. 2005) to date has examined the effectiveness of TT on walking function. This review reported equivocal evidence for the effect of TT on coordination of gait components with randomized controlled trials (RCTs) reporting mixed results on these measures (Moseley et al. 2005). However, this review focused on the effects of TT alone (not all task-specific practice i.e. also including OG interventions) on measures of overall mobility. While data reflecting gait coordination was reported for all studies which included such measures, these data were not included in the meta-analyses which focused on broader dependence in walking, walking speed and endurance. Therefore a systematic examination of existing evidence for the effects of walking practice on the restoration of deficits in gait coordination is needed.

There is at present no review that examines the effectiveness of task-specific locomotor practice interventions specifically aimed at improving coordination during walking and turning in chronic stroke patients. Coordination may be trained as part of the overall walking pattern rather than being targeted specifically. However, clear evidence of characteristic coordination deficits following stroke is emerging, which justifies the practice of using targeted interventions to remediate these deficits. Therefore, the first aim of this review is to identify the range of interventions which are used in adjunct to locomotor practice paradigms in order to specifically target the coordination of walking and turning. This will indicate what treatments currently exist, the theoretical basis on which they are derived and identify where gaps in either theoretical basis or intervention design exist. The second aim of the review is to explore the effectiveness of current interventions on restoring coordination during walking and turning following stroke.

An initial scoping review has revealed very few studies focusing on interventions specifically aimed at improving coordination of axial segments and lower limbs while turning and failed to yield any systematic reviews on the topic. Therefore the search was initially wide, including non-randomised studies and coordination interventions for walking in general.

Objectives

To determine the current best available evidence in regards to task specific locomotor practice interventions for stroke subjects to improve:

1) Coordination of axial segments (head, trunk and pelvis) and stepping patterns during *walking*
2) Coordination of axial segments (head, trunk and pelvis) and stepping patterns specifically while *turning* during walking

Question to be answered:

- What types of interventions are used in adjunct to locomotor practice paradigms in order to specifically target the coordination of walking and turning?
- What is the effectiveness of task-specific locomotor training interventions in improving coordination of axial segments and lower limbs following stroke?

Criteria for considering studies for this review

Types of studies

This review included all types of quantitative studies if they reported results containing measurements of kinematics and will not be restricted to randomised controlled

trials. For the purpose of answering the question regarding the range of adjunct therapies used to address gait coordination in this review, we were inclusive with regard to study design. This allowed us to source all the existing and potential task-specific interventions for locomotor coordination. We included randomised and quasi-randomised controlled trials, case-control studies, cohort studies, and before and after studies which investigate the degree or extent of a physiological condition, or mechanisms of deficits. We included biomechanical modelling or computational modelling papers only if they included data on kinematics of real movements. Studies included must have reported information about segment position, displacement, or their derivatives. Studies, where the primary objective was to investigate CNS control of walking or turning, were included if they revealed biomechanical information about the movement. However, the review will not discuss the findings regarding CNS control. Animal studies were excluded, as the biomechanics of walking in animals are different to that of humans. Studies must have included an intervention or experimental manipulation targeted to improve or elucidate changes in locomotor coordination.

Types of participants

Participants with a clinical diagnosis of stroke –‘ a syndrome of rapidly developing symptoms and signs of focal, and at times, global, loss of cerebral function lasting more than 24 hours or leading to death, with no apparent cause other than that of vascular origin’(WHO 1989) – were included regardless of lesion site, co-morbidities, previous strokes, where intervention is carried out or initial motor impairment. Data on these variables were collected and documented, and used to characterise samples.

Only studies involving participants with “chronic stroke” i.e. greater than 6 months since stroke onset were considered. Despite evidence (Hesse 1994; Peurala 2005; Plummer et

al. 2007) that many stroke patients can overcome persistent disability longer than 6 months after stroke, only one fifth of people more than six months after stroke receive rehabilitation to meet their needs (Health 2007). Stroke is a condition that can improve over many years and "good quality, appropriate, tailored and flexible rehabilitation" is needed to facilitate long-term recovery and reduce long-term disability (Health 2007). However, a recent Cochrane systematic review shows insufficient evidence that "therapy based rehabilitation" is effective for people more than 6 months after stroke (Aziz 2008). Therefore, research is needed to explore if specific interventions are effective, in improving locomotor coordination in this particular patient group.

Studies that also recruited participants with other neurological disorders were included if the data on stroke subjects could be extracted from the data of non-stroke subjects (i.e. data from different groups should not be pooled). Subjects must have had a movement deficit in the axial segments (head, trunk and/or pelvis) or lower limbs (as indicated by clinical measures of stroke recovery and/or gait analyses). We included subjects with other additional stroke-related movement deficits (e.g. of the upper limb).

Types of intervention

Studies must have included an intervention or manipulation aimed at improving or elucidating changes in locomotor coordination of axial segments and lower limbs during walking. For the purposes of this review, we have defined coordination as 'the ability to manage interaction between movements of different body segments for the production of purposeful movement'. Studies must have had a specific design objective related to this definition of coordination of axial segments and lower limbs. Interventions aimed at improving the whole task of walking or individual components of walking, which did not

have a specific data regarding coordination of axial segments or the lower limbs, were excluded. We included studies examining interventions which were aimed at improving overall walking or turning ability if they reported measures of axial segment or lower limb coordination. The intervention must have occurred in walking, either TT or OG walking. The intervention could also include additional elements to augment locomotor training as long as these additional treatment components occur during walking e.g. auditory cueing while walking on a treadmill or BWS. We included studies that used a single intervention, and also studies that delivered a treatment for coordination as part of a complex package. Treatment must have been prescribed, supervised or delivered by an allied health care professional, or delivered as part of a manipulation in an experimental study which investigates the degree or extent of a stroke-related physiological condition. Interventions aimed at improving bilateral lower limb coordination will be included.

Any duration or intensity of programme was included, such as single evaluation sessions and multiple training sessions. Intervention characteristics are described in Table 3 (Characteristics of Design and Intervention).

Types of outcome measures

Since a key motivation of this review was to investigate the range of locomotor training interventions available to improve coordination of movement after stroke and their effectiveness, studies with any measurement of coordination of axial segments and lower limbs were included.

A variety of muscular activation patterns underlying kinematics of walking and turning have been described and some studies have reported that interventions can bring about recovery of functional walking ability without concurrent recovery in muscle activation

patterns (Den Otter et al. 2006; Verheyden et al. 2007; Buurke et al. 2008). The fact that functional recovery has been seen without concurrent restoration of coordination also indicates rehabilitation efforts may be improving compensatory patterns rather than a true restitution of muscular function. Good coordination depends not only on restoration of coordinated activation of muscles but, perhaps more importantly, on the resulting time varying trajectories (kinematics) of segments and their relationship with that of other segments (e.g. swing phase hip, knee, ankle flexion excursion and timing; swing phase knee extension; and stance phase pelvic and knee control) (Wagenaar and Beek 1992; Kwakkel and Wagenaar 2002; Daly et al. 2006). As a result this review excluded studies reporting only electro-myographical measures of coordination and focused on kinematic measures of gait and turning.

Studies which only report gait velocity were not included. While gait velocity can be a function of locomotor coordination (Balasubramanian et al. 2007), the information gait velocity provides regarding underlying impairments is limited (Olney et al. 1994; Lord 1998). Gait speed alone does not represent variables that enable the performance of the coordinated, rapidly repeated, and efficient movements that comprise normal walking (Daly et al. 2007). In addition, gait velocity does not fully reflect all aspects of a typical stroke rehabilitation program such as emphasis on equalization of weight bearing between limbs (Patterson et al. 2008b). While gait speed outcomes will be extracted, studies which report gait speed as the only indicator of coordination were not included.

Measures of coordination to be included:

a. Indices of gait symmetry: Asymmetry in spatiotemporal gait parameters has been commonly used in the clinic to examine the walking patterns in patients who have experienced a stroke (Kim and Eng 2004; Balasubramanian et al.

2007). Asymmetries in spatiotemporal, kinematic, and kinetic parameters of walking have been related to disturbances in motor coordination (Olney and Richards 1996). Specifically, previous studies have reported that temporal asymmetry is strongly correlated with stages of motor recovery, walking speed, lower-extremity muscle strength, peak torque, total work, spasticity and falls, albeit to varying degrees (Brandstater et al. 1983; Titianova and Tarkka 1995; Hsu et al. 2003; Patterson et al. 2008a).

b. Step width & length: Studies presenting measures of these gait parameters will be included as measures of symmetry, indication of improved paretic limb impairments and coordination between limbs can be determined *if* these measures are presented for *each* limb.

c. Gait phase durations (swing, stance, single limb support and double stance durations): Studies presenting measures of these gait parameters will be included as measures of symmetry, indication of improved paretic limb impairments and coordination between limbs can be determined *if* these measures are presented for *each* limb

d. Cross correlations of lower limb or axial segment displacement, velocity or acceleration trajectories or measures of relative phase:

    i. Interlimb phase relationships can be determined by cross-correlating limb angles (Reisman et al. 2005). The lag time at the peak in the cross-correlation function calculated between the two limb angles reveals the degree of coordination between limbs with legs moving reciprocally when the interlimb phase is 0.5 (Reisman et al. 2005).

ii. One critical gait characteristic is the consistency of relative coordination between hip and knee movements (Field-Fote 2002). In stance phase, normal coordination of the relative movement between hip and knee allows the centre of mass to be progressed forward over the stance limb in a stable manner (Daly et al. 2007). Some researchers (Daly et al. 2007; Ford et al. 2007b) have employed a relative motion plot for the hip and knee as a graphical representation of coordination between hip and knee movement.

iii. Angular displacement of body segments can also be used to determine the phase and frequency coordination between segments, this is a measure known as point estimates of relative phase (Donker 2001).

2) Coordination measures that exist within functional measurement scales such as the Fugl-Meyer Assessment of Sensorimotor Recovery after Stroke (Lower extremity section) (Fugl-Meyer et al. 1975).

3) Specific measures of turning ability such as:

i. number of steps to turn, time to turn, stepping strategy and axial segment onset latencies

ii. Berg Balance scale (Berg 1989) (turning items)

1. Number of steps to turn
2. Time to turn
3. Weight shift ability

The types of measurements used were documented and described (see Tables 2.4 & 2.5). Studies which describe movements by visual observation were not included. Studies must use some kind of instrumentation to obtain measurements. Studies which measure other

body movements involved in balance or functional mobility (e.g. sit to stand or responses to platform perturbations) were only included if they also reported one or more of the measures of interest, above.

Search methods for identification of studies

The following databases were searched:

- Cochrane Stroke Group Trials Register
- Cochrane Central Register of Controlled Trials (CENTRAL) (The Cochrane Library, latest issue)
- MEDLINE (1950 to present)
- EMBASE (1980 to present)
- CINAHL (1982 to present)
- AMED (1985 to present)

The grey literature search included:

- National Institutes of Health (NIH) Clinical Trials Database *host:* NIH (http://clinicaltrials.gov/ct)
- National Institute of Clinical Studies (http://www.med.monash.edu.au/healthservices/cce/index.html

We also searched the following physiotherapy and occupational therapy databases:

• Otseeker (http://www,otseeker.com/);

• OT Search (http://www.aota.org/otsearch/index.asp)

•Physiotherapy Evidence database (PEDro, http://www.pedro.fhs.usyd.edu.au/index.html), Chartered Society of Physiotherapy Research Database;

• REHABDATA (http://www.naric.com/research/rehab/default.cfm)

The search strategy, used a combination of controlled vocabulary (MeSH) and free text terms, and was used for MEDLINE and modified to suit other databases (see Appendix I & II).

Methods of the review

Identification of relevant trials

Two of the review authors (KH, PvV) independently read the titles of the identified references and eliminated any obviously irrelevant studies. We then obtained the abstracts for the remaining studies and, based on the inclusion criteria (types of studies, types of participants, aims of interventions, outcome measures), two review authors (KH, PvV) independently ranked these as 'possibly relevant', or definitely irrelevant'. If both review authors identified a trial as 'definitely irrelevant' we excluded this trial at this point. We retrieved the full text of trials categorised as 'possibly relevant', reviewed them, and classified them as 'include', 'exclude' or 'unsure'. If both reviewers were unsure if an article should be included we discussed the article between all three authors until some agreement was reached. We excluded trials classified as 'exclude' by both review authors. If there was a disagreement between review authors, or a decision could not be reached, we sought consensus through discussion, including a third review author if necessary (TP).

Documentation of methodological quality

Two review authors independently assessed the methodological quality of the studies using a standardised critical appraisal assessment. A modified version of the Joanna Briggs Institute (JBI) (Joanna Briggs Institute 2008) critical appraisal checklist form for cohort/case

control was used to assess methodological quality (Appendix III). For rigour and detail, additional questions about quality were included from the checklist for assessment of the methodological quality described by Downs and Black, (1998):

1)Is the hypothesis/aim/objective of the study clearly described?

2)Is there a sound theoretical basis on which the hypothesis is based?

3)Are the characteristics of the people included in the study clearly described?

4) Is the experimental design reliable & valid?

   a. Randomization or counterbalance of intervention or experimental manipulation
   b. Baseline comparisons between groups or conditions
   c. Control condition/group comparisons or Pre-post comparisons
   d. Blinding (where applicable)

5)Were outcomes measured in a reliable way?

4) Were outcomes measures valid?

5) Was appropriate statistical analysis used?

6) Were the main findings of the study clearly described?

Each question was answered as either ‘yes’, ‘no’, or ‘unclear’ and entered into Table 2.2a.

Data extraction

Two review authors independently extracted data from the studies using a standard data extraction form. Where possible we documented:

1) participant details (including age, gender, type of stroke, time since stroke, initial lower limb and axial segment impairment, co-morbid conditions, premorbid disability)
2) sample size

3) the inclusion and exclusion criteria for recruitment of patients, and sampling frame for participant selection
4) a description of the coordination/walking intervention (including whether delivered as part of a package of treatment or as a specific intervention, and whether it is directed specifically at coordination while turning, or towards coordination in walking more generally)
5) the duration/intensity/frequency of intervention
6) setting in which the intervention was delivered
7) the comparison intervention, if there was one or pre and post comparisons in non-control condition studies
8) person delivering the intervention and their qualifications and experience
9) the outcome measurement used to describe coordination
10) the outcome measurement used to describe of functional locomotor abilities

Data extracted were entered into Tables 2.4 & 2.5. Details of locomotor training (overground walking and/or repeated turning, treadmill walking, treadmill walking with body weight support and/or robotic machines, any walking practice with augmented feedback such as auditory cueing, etcetera) was entered into Table 2.3.

If a study included an experimental manipulation or condition as opposed to a direct intervention it was still included. For example, repeated trials of walking overground was considered to be locomtor practice.

Data synthesis

Details of the included studies were recorded in tables, with details of the above items in the data extraction list. Descriptive statistics were used to summarise the findings.

Frequencies of items of interest were recorded, including number of studies with coordination interventions for lower limb and those for axial segment control, number of studies that found a difference in outcome between the coordination intervention and another group (no treatment, placebo, or alternative intervention). Means and standard deviations were reported where appropriate, e.g. mean age of subjects, mean time since stroke and mean duration of treatment.

Meta-analysis was only to be conducted if included studies were similar enough to each other so that generalisation of results would be valid (Joanna Briggs Institute 2008). The four main criteria that considered for similarity were (Joanna Briggs Institute 2008):

• patient population (we have restricted our inclusion criteria to only chronic stroke patients with the aim of improving homogeneity of patients to permit meta-analyses)

• outcome (eg. is it valid to combine studies that have calculated measures of coordination in different ways i.e. gait symmetry and/or combine different measures of coordination i.e. relative phase and inter-limb phase relationships?)

• intervention (eg. are the interventions being given to the 'treatment' group in each study similar enough to allow meta-analysis? We have restricted our inclusion criteria to only studies employing locomotor training interventions in order to facilitate meta-analyses)

• control (eg. are the control groups in each study receiving treatment similar enough to warrant combination and meta-analysis?)

Comparative statistical analyses would only be performed if authors judge that included non-randomised studies were both reasonably resistant to biases and relatively homogeneous in this respect (Taggart et al. 2001). Should meta-analyses have been warranted Hedges' standardised mean difference would be used for all continuous measures as it includes an adjustment to correct for small sample size bias (Deeks 2006). Meta-analysis would be

performed using both fixed-effect and random-effects modelling to assess sensitivity to the choice of modelling approach.

A subgroup of studies specifically investigating coordination while turning during walking was to be extracted and the above information for these tabulated and presented separately. The interventions for turning coordination were to be contrasted and compared to the interventions for coordination in straight walking.

Results

The search strategy identified 1132 titles (see Figure 2.1). After elimination of duplicates and obviously irrelevant titles, 586 'possibly relevant' abstracts remained. These abstracts were obtained and two review authors (KH and PvV) independently assessed them for inclusion. Where disagreements or uncertainties arose, the opinion of a third reviewer was sought (TP). One-hundred and forty-five abstracts were assessed as 'include' and the full papers for these studies were obtained. A total of 134 studies were excluded following consideration of the full papers, leaving 11 studies included (see Appendix IV: Characteristics of included studies). Reasons for exclusion were (see Appendix V: Characteristics of excluded studies): no intervention (32 studies) e.g. feasibility studies, reviews, or studies seeking to quantify the relationship between coordination and functional walking capacity; not stroke population (four studies) e.g. studies which pooled data from participants with a range of neurological diseases and injuries; insufficient coordination measures (37 studies) e.g. gait parameters averaged across both paretic and non paretic limbs or no kinematic data; no aim to establish the effects of intervention or manipulation on locomotor coordination (29 studies) e.g. an intervention (such as current practice) or experimental manipulation is employed but the intention is not to establish the effects on locomotor coordination (but, for

example, to document recovery); acute patients only (12 studies); interventions other than locomotor practice (19 studies) e.g. ankle-foot orthotics, botox, imagery, exercise; and duplicates (one study).

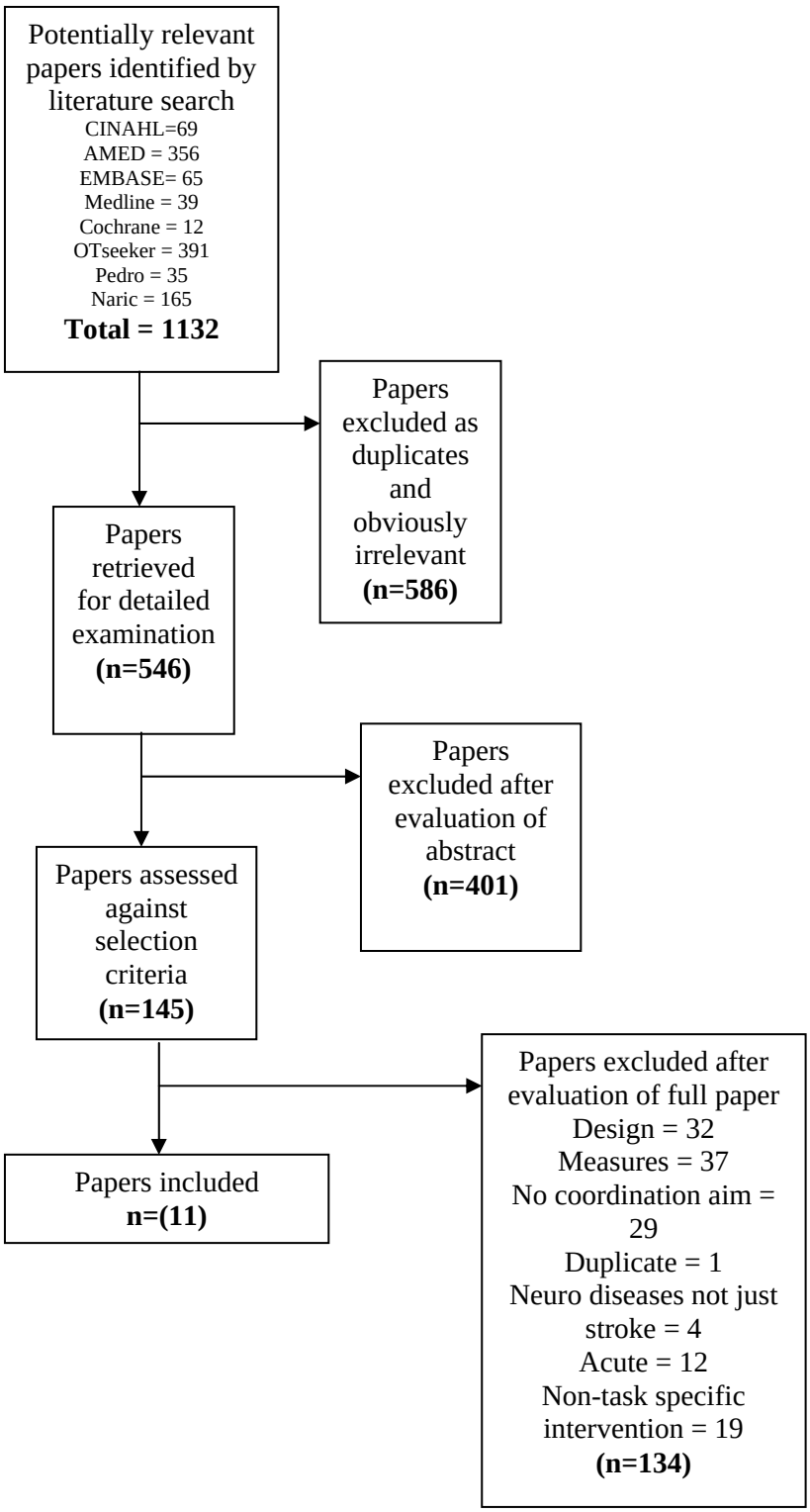

Figure 2.1: Illustration of studies identified and their management

Turning studies

Two studies (Lamontagne et al. 2007; Lamontagne and Fung 2009) investigating stroke-related coordination impairments during turning while walking were identified. However, these studies were excluded from review because the experimental designs did not allow comparisons to establish the efficacy of experimental manipulations on coordination, i.e. not cohort studies or before and after studies permitting control or pre-post comparisons. These studies will not be discussed in this review as they did not meet criteria for inclusion but will be discussed in later chapters.

Included studies

Eleven studies (163 stroke participants) met the inclusion criteria for this review (Waagfjord et al. 1990; Harris-Love et al. 2001; Chen et al. 2005a; Ford et al. 2007a; Lindquist et al. 2007; Plummer et al. 2007; Reisman et al. 2007; Roerdink et al. 2007; Yang et al. 2007; Hornby et al. 2008; Westlake and Patten 2009). A brief overview of the studies is presented below. Full descriptions of the included studies can be found in the in Table 2.1 (Demographics of included participants).

Table 2.1 Demographics of included participants (mean, [range], {SD}) RA= robot assisted, TA = therapist assisted

									Initial measures of impairment		
	Study	sample size	Male: female	age in years	Rparetic: Lparetic	type of stroke	time since stroke in months	final number of participants analysed	Fugl-Meyer (max 36)	Berg Balance (max 54)	Walking Speed (m/s)
1	Chen, 2005	6	03:03	60 {7} [52-68]	03:03	unspecified	44 {41} [8-122]	6	21 {4}		0.52 {0.22}
2	Ford, 2007	11	10:01	[14-78]	05:06	unspecified	>1yr	11			0.877 {0.36} [0.63-1.52]
3	Harris-Love, 2001	18	12:06	unspecified	07:11	unspecified	39.5 {32} [4.5-121]	18			0.54 {0.2}
4	Hornby, 2008	48	30:18	57 {11}	32:16	ischemic, or hemorrhage.	50 {51} RA, 73 {87} TA	34		43 {10} RA, 42{10} TA	0.45 {0.19} RA, 0.43 {0.22} TA
5	Lindquist, 2007	8	06:02	56.6 {10.26}	02:06	ischemic or hemorrhage	17.3 {10.9}	8			0.43 {0.19} [0.2-0.6]
6	Plummer, 2007	7	03:04	54.7 {15.4} [32-73]	03:04	unspecified	5.14 {1.21} [4-7]	6	21 {4} [15-23]	39.8 {15.5} [14-54]	0.39 {0.22} [0.13-0.67]
7	Reisman, 2007	13	09:04	51.77 {12.00} [27-70]	07:06	single	52.07 {56.34} [7-192]	13	25.7 {5.8} [15-33]		1.13 {0.31} [0.66-1.7]
8	Roerdink, 2007	10	08:02	63 {11.9} [46-78]	10:03	first, infarct	37.7 {32.67} [3-104]	9	24.9 {6.6} [16-32]		0.859 {0.182} [0.667-1.31]
9	Waajford, 1990	1	00:01	40	00:01	thrombus in the right MCA	36	1			0.76 {0.02}
10	Westlake, 2009	16	13:03	58.6 {16.9} RA, 55.1 {13.6} TA	07:09	ischemic and hemorragic	43.8 {26.8} RA, 36.8 {20.3} TA	16	23 {4.3} RA, 21.4 {5.1} TA		0.62 {0.31} RA, 0.62 {0.28} TA
11	Yang, 2007	25	14:11	59.17 {11.98} [45-80] control, 59.46 {11.83} [47-76] dual task	16:09	single	56.16 {88.8} [12-336] control, 48.96 {37.56} [13.2-114] dual task	25			0.92 {0.31} control, 0.85 {0.19} dual task

Design

Two of the 11 included studies were randomised controlled trials (Yang et al. 2007; Hornby et al. 2008). One of the included studies was a pilot RCT (Westlake and Patten 2009), and another is a pilot/feasibility study with no randomised assignment (Plummer et al. 2007). Two studies (Waagfjord et al. 1990; Plummer et al. 2007) were ABA case-series design. The remaining studies were multi-factorial experimental designs. Within these studies only one (Roerdink et al. 2007) randomised participants to different orders of treatment/experimental manipulation. Despite not being appropriate for incorporation in meta-analyses these studies met the inclusion criteria for this review. Details of all studies are summarised in Table 2.1 (Demographics of included participants) and in Table 2.2 a & b (Non-randomised Study Methodological Quality Summary & Randomised Study Methodological Quality Summary).

Comparison Groups

Three experimental studies (Harris-Love et al. 2001; Chen et al. 2005a; Ford et al. 2007a) made comparisons between experimental conditions and control conditions and two studies (Waagfjord et al. 1990; Plummer et al. 2007) contributed evidence from pre-post comparisons. Lindquist et al, (2007) employed an ABA design but rather than being no treatment in phase A, the comparison is made between BWSTT in phase A1 and A2 and BWSTT +FES in phase B, hence using BWSTT as a control intervention. Two further experimental studies (Reisman et al. 2007; Roerdink et al. 2007) employed control groups of healthy participants. However, for the purposes of this review only comparison within stroke groups address the research questions. Therefore, these two studies contribute evidence to the review by comparisons made within the group of participants with stroke, between experimental and control conditions respectively of auditory paced treadmill walking and

non-paced treadmill walking (Roerdink et al. 2007) and treadmill walking vs split treadmill walking (Reisman et al. 2007). The majority of studies employed designs in which participants acted as their own control, hence equality of baseline characteristics is controlled for (and therefore this item is not present in Table 2.2 a (Non-randomised Study Methodological quality summary)). Three studies, two RCTs (Yang et al. 2007; Hornby et al. 2008) and one pilot RCT (Westlake and Patten 2009), derived evidence from comparison between participants in experimental and control *groups*. A summary of experimental design and comparison groups for all studies can be found in Tables 2.2 & 2.3 (Non-randomised Study Methodological Quality Summary & Randomised Study Methodological Quality Summary & Characteristics of Design and Intervention).

Table 2.2a: Non-randomised Studies Methodological Quality Summary

					experimental design			outcome measures			
	study	aims	theoretical basis	baseline characteristics described	randomized order of trials	control condition	Blinding of assessor	reliable method	valid	appropriate statistics	findings well described
1	Chen, 2005	yes	yes	yes	unclear	yes	no	yes	yes	unclear	unclear
2	Ford, 2007	yes	yes	no	no	yes	no	yes	yes	yes	unclear
3	Harris-Love, 2001	yes	yes	no	no	yes	no	yes	yes	yes	yes
5	Lindquist, 2007	yes	yes	yes	no	yes	no	yes	yes	yes	yes
6	Plummer, 2007	yes	yes	yes	no	no	no	yes	yes	unclear	yes
7	Reisman, 2007	yes	yes	yes	no	yes	no	yes	yes	yes	yes
8	Roerdink, 2007	yes	yes	yes	yes	yes	no	yes	yes	yes	yes
9	Waajford, 1990	yes	yes	unclear	no	no	no	no	unclear	yes	yes

Table 2.2b: Randomised Studies Methodological Quality Summary

	study	allocation concealment	blinding of outcome assessor	intention to treat analysis	baseline similarity
4	Hornby, 2008	yes	no	no	yes
10	Westlake, 2009	unclear	unclear	yes	yes
11	Yang, 2007	yes	unclear	yes	yes

Intervention

Each of the studies included compared effects of different experimental and control treatments, (as opposed to experimental treatment versus no treatment). All studies except for two (Waagfjord et al. 1990; Harris-Love et al. 2001) employed interventions which were augmentations to basic TT or OG locomotor training in an aim to effect gait coordination. Intervention augmentations include auditory cueing (Ford et al. 2007a), BWS (Chen et al. 2005a), BWS +FES (Lindquist et al. 2007), BWS +OG (Plummer et al. 2007), robot assisted TT (Hornby et al. 2008; Westlake and Patten 2009) split belt TT (Reisman et al. 2007) and dual task walking (Yang et al. 2007). Control comparisons ranged from pre-post comparisons (Waagfjord et al. 1990; Plummer et al. 2007; Reisman et al. 2007) to free TT(Chen et al. 2005a; Roerdink et al. 2007), OG (Harris-Love et al. 2001; Yang et al. 2007), therapist assisted TT (Hornby et al. 2008; Westlake and Patten 2009) and stepping to an auditory cue (Ford et al. 2007a). Only two studies (Waagfjord et al. 1990; Harris-Love et al. 2001) employed interventions of solely TT as the experimental treatment. Interventions ranged from one session including a few repetitions or set period of time of walking to 36 sessions of locomotor training. A summary of intervention content for all studies can be found in Table 2.3 (Characteristics of Design and Intervention).

Table 2.3: Characteristics of Design and Intervention

	Study	Study design	Intervention group	Intervention content	comparison (e.g. experimental vs control condition or pre - post)	Duration/intensity/frequency	Setting
1	Chen, 2005	multifactorial experimental design	control	treadmill walking	experimental conditions are different BWS TT parameters vs. control of free TT	1 session of 20 seconds walking in each of 10 conditions	USA
			experimental treatment 1	BWS 20,35 or 50%			
			experimental treatment 2	stiffness 11.7 or 35.1			
			experimental treatment 3	speed 70, 100, or 130% of OG			
			experimental treatment 4	hand rail hold			
2	Ford, 2007	simple experimental design (condition 1 vs condition 2)	control	step to the beat on treadmill	compare experimental treatment to control	1 session of 30 seconds walking in each condition	USA
			experimental treatment	move arms and legs to the beat on treadmill			
3	Harris-Love, 2001	simple experimental design (condition 1 vs condition 2)	control	OG walking	control comparison to OG	5 trials of each condition	USA
			experimental treatment	TT			

4	Hornby, 2008	RCT	control	Therapist assisted TT	control comparison to therapist assisted TT	12 sessions, 30 mins,	USA
			experimental treatment	Robot assisted TT			
5	Lindquist, 2007	ABA single case series	control A1	BWS TT	BWS TT only (phase A) compared with BWS TT+FES (phase B) in ABA fashion	27 sessions (3 days per week for 9 weeks), each session lasting 45 minutes.	Brazil
			experimental treatment (B)	BWS TT + FES			
			control A2	BWS TT			
6	Plummer, 2007	pilot/feasibility study	control	none	ABA comparison	BWS for 20 to 30 minutes (excluding rest time) treadmill was followed immediately by 10 to 15 minutes of overground training and home exercise instruction. 3 days per week for a total of 36 sessions for max 16 weeks.	USA
			experimental	BWS TT +OG			
7	Reisman, 2007	multifactorial experimental design with stroke group vs healthy controls.	control	healthy participants	Split-belt walking compared to control of fixed belt within stroke and pre and post split-belt comparisons	2 testing sessions of: Baseline; 2 min (tied slow), 2 min (tied fast), 2 min (tied slow). Adaptation; 15min, treadmill belts split (one fast, one slow). Post-adaptation; 6min, tied slow configuration.	USA
			experimental	split belt TT			

8	Roerdink, 2007	multifactorial experimental design with stroke group vs healthy controls.	control	TT	comparison to no pacing condition within stroke participant group only	90 seconds at 3 belt speeds, acoustic pacing for 3 minutes, 60 seconds at preferred stride frequency	Netherlands
			experimental	auditory cueing on TT			
9	Waajford, 1990	case report ABA comparison	control	pre-test only	ABA comparison	10 mins 3 times/wk, 3 weeks	USA
			experimental	TT			
10	Westlake, 2009	pilot RCT	control	Therapist assisted TT	compare to control of therapist assisted	12 sessions (3×/wk over 4 weeks) involving 30 min of stepping per session	USA
			experimental	Robot assisted TT			
11	Yang, 2007	RCT	control	single task OG	control comparison to single task OG walking	30 minutes of a ball exercise program 3 times a week for 4 weeks or control of variable walking practice	Taiwan
			experimental	dual task OG	measures taken in both a single task and dual task gait analysis paradigm		

Sample sizes

On average, studies included 14 stroke patients. This ranges from just 1 participant (Waagfjord et al. 1990) to 48 (Hornby et al. 2008) see Table 2.1 (Demographics of included participants). Half of the included studies utilized interventions which exceeded one session in duration. However, attrition was only seen in 3 studies. Attrition was only a significant feature of one RCT(Hornby et al. 2008) with 14 of 48 patients lost to follow up. Each of the Roerdink (2007) and Plummer (2007) studies had one participant who did not complete either all training sessions (Plummer et al. 2007) or all testing conditions (Roerdink et al. 2007).

Setting

All studies were carried out in the USA apart from one in Taiwan (Yang et al. 2007), Netherlands (Roerdink et al. 2007) and Brazil(Lindquist et al. 2007); see Table 2.3 (Characteristics of Design and Intervention).

Participants

Demographics of participants are provided in Table 2.1. Of the participants 33.7% were female. The lowest reported age was 14 years (Ford et al. 2007a) and the highest mean (SD) age was 63 (11.9) years (Roerdink et al. 2007). Across the studies time since stroke varied from a mean (SD) of 73 (87) months (Hornby et al. 2008) to a mean (SD)of 5 (1.21) months (Plummer et al. 2007). One study did not report time since stroke, except to say participants were greater than 1 year post-stroke (Ford et al. 2007a). Side of stroke was reported in all studies; 65 participants had a right hemisphere stroke and 98 participants had a left hemisphere stroke. All studies reported baseline walking speed, indicating the majority of participants could be classed as having initial moderate gait speed impairment (>0.4m/s and

<0.8m/s) (Plummer et al. 2007). Three studies (Ford et al. 2007a; Roerdink et al. 2007; Yang et al. 2007) reported baseline mean self-selected walking speeds greater than 0.8 m/s indicating unlimited community ambulation capacity (Perry et al. 1995). One study (Reisman et al. 2007) reported fast over-ground walking speed as opposed to self selected pace. No studies reported mean initial gait speeds of less than 0.4m/s.

Outcome measures

As anticipated, a variety of outcome measures were used by the included studies. All of the studies included a measure of gait speed and all but one study (Ford et al. 2007a) reported some measure of either temporal or spatial gait symmetry. However, every study calculated indices of symmetry differently; see Table 2.4 (Summary of Clinical Outcome Measures) & 2.5 (Summary of Coordination Outcome Measures). It was apparent, therefore, that due to differences in the mathematical derivation of symmetry as an index of coordination, it would be inappropriate to combine this outcome together within statistical analyses.

Risk of bias in included studies

For full details of methodology and risk of bias assessments see Tables 2.2 a&b (Methodological quality summary). Only two studies included were RCTs and a further pilot RCT. The remaining studies were experimental designs with only one study (Roerdink et al. 2007) randomising the order of treatments to participants and all studies employing designs in which participants acted as their own control (i.e. comparison to control conditions, as opposed to groups, and pre-post test comparisons). As a result, most of the included studies were judged to be of poor or uncertain methodological quality according to the combined JBI and Downs & Black (1998) checklists (summarised in Tables 2.2 a&b). All studies were

therefore judged to be at high risk of bias. The studies included have little attrition and so intention-to-treat analysis is not featured. While outcome assessors were not blind to the study aims in the 7 non-randomised studies, outcome assessment are conducted using physical measurements taken according to standardized protocols and unbiased measurement systems (e.g. three-dimensional motion analysis systems) in effort to minimize detection bias (concerning unbiased and correct assessment of outcome, including blinding of assessors) (Joanna Briggs Institute 2008; Higgins 2009). Concealed randomised allocation procedures are not utilised in any of the seven non-randomised studies included. However, systematic differences between characteristics of participants in different intervention 'groups' are countered in each of the non-randomised studies, to some extent, by employing experimental designs in which participants act as their own control. All studies with non-randomised designs were unable to blind researchers/therapists or participants and did not employ pre-written protocols and therefore were deemed to be at high risk of performance bias(concerning the fidelity of the interventions, and quality of the information regarding who received what interventions, including blinding of participants and healthcare providers) and reporting bias (concerning publication biases and selective reporting of results) (Joanna Briggs Institute 2008; Higgins 2009).

The RCT by Hornby et al, (2008) utilised envelop concealed randomisation stratified according to baseline gait speed but did not blind outcome assessors to allocation. Groups were similar at baseline but only data from 34 participants who completed training, out of 48 randomised, were analysed. The RCT by Yang et al, (2007) utilised independent randomisation in concealed envelopes. The control group did not receive any rehabilitation and therefore groups were not treated equally and it is not stated whether or not outcome assessor(s) were blind to allocation. Groups were equal at baseline and no dropouts were

reported. The pilot RCT by Westlake et al, (2009) assigned participants to groups using computer generated random order. However, the allocation was only concealed from study personnel until after baseline testing. There were no significant differences between groups at baseline and all participants completed the study.

Table 2.4: Summary of Clinical Outcome Measures (mean {SD}[range])

	Measure:	Fugl-Meyer LE (max 34)				Berg Balance Scale (max 56)						Self selected gait speed (m/s)					
	Time point:	baseline		time point 2		baseline		time point 2		time point 3		baseline		time point 2		time point 3	
Study	Condition	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	Chen, 2005	21{4}										0.53 {0.22}					
2	Ford, 2007											0.877 {0.36} [0.63-1.52]					
3	Harris-Love, 2001																
4	Hornby, 2008,					42 {10}	43 {10}	44 {11}	44 {10}	46 {8.9}	45 {10}	0.43 {0.22}	0.45 {0.19}	0.56 {0.28}	0.52 {0.21}	0.52 {0.25]	0.50 {0.21}
5	Lindquist, 2007																
6	Plummer, 2007		20.6 {4.4}		21.3 {6.8}		37.8 {15.9}		43.6 {15.8}				0.39 {0.22}		0.655 {0.36}		
7	Reisman, 207	25.7 {5.8}										1.13 {0.31} [0.66-1.7]					
8	Roerdink, 2007																
9	Waajford, 1990												0.76 {0.02}		0.79 {0.02}		
10	Westlake, 2009	21.4 {5.1}	23 {4.3}	22.4 {5.2}	25.6 {5.0}	47.0 {7.0}	46.9 {7.5}	51.0 {5.4}	48.3 {6.8}			0.62 {0.28}	0.62 {0.31}	0.65 {0.29}	0.72 {0.38}		
11	Yang, 2007											0.92 {0.31}	0.85 {0.19}	0.79 {0.15}	1.15 {0.18}		

Table 2.5: Summary of Coordination Outcome Measures: (mean {SD}[range]). Condition A represents control conditions, condition B represents experimental conditions. Data from Reisman, 2007 & Ford , 2007 presented in results text.

			temporal asymmetry				spatial asymmetry					
			baseline		time point 2		baseline		time point 2		time point 3	
Study	symmetry measure	calclulation of symmetry	A	B	A	B	A	B	A	B	A	B
Chen, 2005	temporal and spatial	Asymmetry % = 100* (Vparetic-Vnon paretic)/ max (Vparetic, Vnon paretic) positive (negative) index indicates a larger value of the gait parameter for the paretic (non-paretic) limb										
	swing time	%	43.4 {16.5}	22.7 {25.5}								
	step length	%					27.4 {56.3}					
	step length	calculated from raw data (non-paretic/paretic)					0.75					
Harris-Love , 2001	temporal: relative temporal phasing	(paretic step-time/cycle time) (%of cycle)	59	55								
	Stance time	difference in stance time between limbs (%of cycle)	14.38 {8.23}	7.27 {5.30}								
	Single-limb support time	difference in single limb support time between limbs (% of cycle)	14.54 {8.26}	7.25 {5.29}								
	Stance: swing ratio	difference in stance to swing ratio between limbs (% of cycle)	1.76 {1.65}	0.82 {0.75}								
Hornby, 2008	spatial : step-length	100* (unimpaired step-length/impaired step -length) 100% indicating perfect symmetry					75 {21}	71 {24}	79 {18}	75 {22}	79 {19}	71 {20}

Lindquist, 2007	total cycle time	(unaffected cycle length/affected cycle length) *100 =%	89.36 {0.1}		84.69 {0.1}	94.26 {0.1}						
	swing time		62.07 {0.2}		71.25 {0.2}	78.17 {0.2}						
	stance time		89.89 {0.1}		91.44 {0.2}	89.34 {0.1}						
Plummer, 2007	spatial symmetry: step-length	calculated from raw data (non-paretic/paretic)						0.88 {0.24}		0.77 {0.25}		
Roerdink, 2007	spatial and temporal: step-ength and time	%asymmetry [(Vparetic Vnonparetic)/max(Vparetic,Vnonparetic)] 100. index of 0 indicates perfect symmetry. A positive index indicates a larger step time or step length for the paretic limb	26.5	22.1			17	12				
	Spatial: step-length	calculated from raw data (Non-paretic/paretic)	0.72	0.76			0.85	0.91				
Waajford, 1990	spatial: step-length	pearson product correlation between left and right step-lengths						-0.258		0.753		
		difference in area under left and right step-lngth curves (symmetrical steps = 0)						72.6		42		
	Spatial: step-length	calculated from raw data (non-paretic/paretic)						0.83		0.87		
Westlake, 2009	spatial: absolute step-length	SLRabs=ABS[1−(P step-length/NP step-length)] range 0 to 1, with an index of 0 reflecting perfect symmetry					0.39 {0.37}	0.53 {0.58}	0.34 {0.35}	0.37 {0.46}		
Yang, 2007	temporal symmetry: single limb support	unaffected single limb support (% of gait cycle)/affected single limb support (% of gait cycle)	1.13 {0.18}	1.12 {0.09}	1.14 {0.16}	1.08 {0.12}						

Effects of Intervention

While meta-analysis is the ultimate goal of a systematic review of quantitative studies, a number of criteria must first be met before the results of different studies can be validly combined. Studies to be included in meta-analysis should be similar to each other so that generalisation of results is valid (Joanna Briggs Institute 2008; Higgins 2009). The studies included in this review were of poor methodological quality (high risk of selection and detection bias with only two studies employing concealed random assignment to groups and only one study reporting blinding of assessors) and similarity of control and experimental interventions was low despite study inclusion criteria restricting studies to only locomotor training programs. However, each study included used a different variation on locomotor training e.g. auditory pacing or BWS. Moreover each study employed a different control condition (e.g. OG walking, TT walking, therapist assisted walking) and crucially different control comparisons (e.g. pre-post test comparisons or comparison to control *conditions* rather than control *groups*). Results from different study designs should therefore be expected to differ systematically, resulting in increased heterogeneity. It was therefore determined that studies which used different experimental designs (or which have different design features), or randomized trials and non-randomised studies, should not be combined in a meta-analysis (Higgins 2009). Although a this review was undertaken in order to allow consideration of non-RCT study designs, meta-analysis is more soundly done when a study designs are homogeneous in design elements which excluded the possibilities of bias (Higgins 2009). Given the methodological quality of the studies included, results of a meta-analysis would be questionable and could well be invalid. Therefore meta-analysis is not performed in this review.

Outcome measures

Temporal Symmetry:

Six studies (Harris-Love et al. 2001; Chen et al. 2005a; Lindquist et al. 2007; Reisman et al. 2007; Roerdink et al. 2007; Yang et al. 2007) reported outcomes of temporal symmetry; see Table 2.5 Summary of Coordination Outcome Measures. All studies, except Yang et al, (2007) reported significant improvements in temporal symmetry indices with the experimental treatment compared to that achieved in the control condition or when comparing pre-post training values.

1. Cycle length symmetry (Lindquist et al. 2007): Lindquist et al, 2007 found a significant increase in total cycle length symmetry with the combination of BWSTT and FES from 84.69% to 94.26% ($p = .004$), only after phase A1 delivery of BWSTT.
2. Overall Temporal Asymmetry (Roerdink et al. 2007): Roerdink et al, 2007 found a significant decrease in temporal asymmetry with auditory pacing from 26.5% (no pacing) to 22.1% (auditory pacing) ($p<.05$). This effect may have been achieved by significantly decreased step time on the paretic side from .75s (no pacing) to .72s (acoustic pacing) ($p<.02$).
3. Swing time asymmetry (Chen et al. 2005a; Lindquist et al. 2007): Chen and colleagues (2005) reported a significant ($p =.03$) reduction in swing time asymmetry from 43.4% in free treadmill walking condition to 22.7% in the harness support condition providing 35% BWS. This study also found a significant reduction in swing time asymmetry with treadmill walking with handrail support and the combination of handrail support and harness support ($p=.03$) but not with increase levels of BWS, harness rigidity or speed. This effect may be the result of increased swing time in the *non-paretic* limb. Lindquist et al, (2007) found significant ($p<.01$) decreases in swing

asymmetry from 37.93% in pre-training to 28.75% in BWSTT phase A1 and a further significant ($p<.01$) decrease to 21.83% with BWSTT +FES in phase B.

4. Single limb support time symmetry (Harris-Love et al. 2001; Yang et al. 2007). Yang et al., (2007) found no significant differences in the symmetry of single limb support time between groups (no rehabilitation practice vs dual task walking practice) when measured under either the single or dual task walking measurement paradigms. Harris-Love et al, (2001) found single limb support time was significantly ($p<.03$) increased on the paretic limb and decreased on the non-paretic limb in the treadmill condition compared to the overground walking condition.
5. Stance time (Harris-Love et al. 2001; Lindquist et al. 2007): Harris-Love et al, (2001) found stance time was significantly ($p<.03$) increased on the paretic limb and decreased on the non-paretic limb in the treadmill condition compared to the overground walking condition. Lindquist et al, (2007) found no significant effects on stance symmetry between BWSTT and BWSTT + FES.
6. Stance to swing ratio (Harris-Love et al. 2001): Harris-Love et al, (2001) found the stance to swing ratio was significantly ($p<.03$) increased on the paretic limb and decreased on the non-paretic limb in the treadmill condition compared to the overground walking condition.
7. Double Support time (Reisman et al. 2007): Resiman et al, (2007) reported a trend ($p = .07$) for double support to become more symmetric following exposure to split belt treadmill training in participants with initially asymmetric double support compared to baseline period of conventional treadmill training.

8. Mean relative temporal phasing (paretic limb step time divided by cycle time with reciprocal stepping being 50%) was reported by Harris-Love et al., (2001) who found a decrease in this measure from 59% in OG and 55% in TM condition ($p = 0.008$).

Spatial Symmetry

Six studies reported measures of step length asymmetry (Waagfjord et al. 1990; Plummer et al. 2007; Reisman et al. 2007; Roerdink et al. 2007; Hornby et al. 2008; Westlake and Patten 2009). Of these six, four studies (Waagfjord et al. 1990; Reisman et al. 2007; Roerdink et al. 2007; Westlake and Patten 2009) reported improved step length symmetry with experimental treatment compared to either control treatment conditions or in pre-post training comparisons.

1. Step length asymmetry (Waagfjord et al. 1990; Plummer et al. 2007; Reisman et al. 2007; Roerdink et al. 2007; Hornby et al. 2008; Westlake and Patten 2009): Reisman et al, (2007) report a significant ($p = 0.01$), improvement between the step length asymmetry in the baseline treadmill walking period compared to the early post-adaptation period following exposure to split treadmill walking with subjects becoming more symmetric in post-adaptation. Roerdink et al, (2007) reported a significant ($p < .05$) reduction in spatial asymmetry 17% in the no pacing condition to 12% in the acoustic pacing condition. Westlake et al, (2009) reported significant ($p<.05$) reduction in step-length asymmetry from .53 at baseline prior to robot assisted TT to .37 following robot assisted TT but no significant differences in step length symmetry between robot assisted TT and therapist assisted TT. In contrast, Hornby et al, (2008) found *no significant effects* of robotic assisted TT compared to therapist assisted TT on step length asymmetry. Plummer et al, (2007) reported differing effects

of combined BWSTT +OG on step length and step length asymmetry according to participants. Some participants increased step length on the paretic limb from baseline to post-treatment while others increased step length on the non-paretic limb. This lead to the result that only one participant demonstrated a large improvement in symmetry between pre and post treatment comparisons while another demonstrated an increased *a*symmetry. Waajford et al, (1990) reported increased step length on the non-paretic limb (allowing longer stance time on the paretic limb) causing improved step-length symmetry following TT compared to pre-training.

Other coordination measures

Relative phase

One study (Ford et al. 2007b) reported measures of relative phase between thorax and pelvis. Instructions to move the arms and legs to the beat of an auditory rhythm led to significantly ($p<.05$) greater transverse thoracic rotation, a corresponding increase in transverse pelvic rotation and lengthening the stride (decreasing stride frequency) as compared to instructions to step to the beat. Furthermore, the mean relative phase was significantly greater when subjects were moving their arms and legs versus *only* stepping to a metronome beat of 1 Hz.

Inter-limb phase relationships

One study (Reisman et al. 2007) reported measures of inter-limb phase relationships. Reisman and colleagues (2007) reported that limb phasing changed significantly ($P< 0.05$) from Baseline (when limbs were seen to be moving reciprocally) to early Adaptation (when there was a phase advancement of the leg on the fast belt) during split belt walking. The new

phase relationship remained after discontinuing split-belt walking, resulting in an after-effect in the Post-adaptation period (comparing baseline to early Post-adaptation, $p<0.01$).

Clinical Outcome measures

Gait speed

All studies, except three (Harris-Love et al. 2001; Lindquist et al. 2007; Roerdink et al. 2007), reported self-selected walking speed (SSWS). Ford et al, (2007b) and Reisman et al, (2007) reported fast OG walking speed and Ford et al, (2007b), Resiman et al, (2007) and Chen et al, (2005a) reported walking speed only as a baseline measure indicating initial walking impairment. Only two studies (Waagfjord et al. 1990; Westlake and Patten 2009) reporting SSWS did not find significant improvements in this measure in experimental conditions compared to control conditions or in pre-post training comparisons. Hornby et al, (2008) reported that the control condition of therapist assisted locomotor training yielded a significantly ($p=.03$) larger increase in SSWS than the experimental condition of robot assisted locomotor training but only at follow-up (6 months after training was completed). The pilot RCT by Westlake and colleagues (2009) contrasting robot assisted locomotor training to therapist assisted locomotor training reported no significant ($p =0.8$) improvement in gait speed between the two intervention conditions. Lindquist et al, (2007) reported a significant ($p<.01$) increase in SSWS after the BWSTT +FES compared to the initial phase of BWSTT only and a significant ($p< .01$) reduction in SSWS in phase A2 (of the A1, B, A2 design) indicating speed was reduced after withdrawal of FES. Plummer et al, (2007) reported increased SSWS following treatment compared to baseline. All participants of this study who had initial gait speeds of >0.4m/s but < 0.8m/s increased gait speed to above 0.8m/s, the threshold for classification as unlimited community ambulatory (Perry et al. 1995). However,

only one participant with initially severe gait speed impairment (<0.4m/s) increased SSWS to above 0.4 m/s. Waajford et al, (1990) reported a trend for *decreasing* walking velocity *during* TT but walking speed post-TT was still greater than pre-TT. Yang and colleagues (2007) reported significant increases in SSWS both in pre and post test comparisons within the experimental treatment group (dual task locomotor training) ($p= 0.001$) and between experimental and control conditions ($p< 0.001$).

Fugl-Meyer

Four studies(Chen et al. 2005a; Plummer et al. 2007; Reisman et al. 2007; Westlake and Patten 2009) reported Fugl-Meyer Assessment of Sensorimotor Recovery after Stroke (Lower extremity section) (Fugl-Meyer et al. 1975). Two of these studies(Chen et al. 2005a; Reisman et al. 2007) reported this measure only as an indicator of baseline impairment. Plummer et al, (2007) reported improvements in FM scores from pre to post BWSTT + OG training in all but one participant. Westlake et al, (2009) reported no significant differences in this measure between robot and therapist assisted lcoomotor training conditions.

Berg Balance Scale

Three studies (Plummer et al. 2007; Hornby et al. 2008; Westlake and Patten 2009) reported BBS scores. While the pilot RCT by Westlake et al, (2009) reported significant ($p<.05$) improvements in BBS scores from pre to post test within *both* control and experimental treatment groups this was not found in the full RCT by Hornby et al, (2008). Plummer et al, (2007) reported improved BBS scores for all participants following BWSTT +OG treatment compared to baseline scores.

Discussion

Summary of main results

Only two RCTs (Yang et al. 2007; Hornby et al. 2008) aimed at improving locomotor patterns and assessing effects of interventions on aspects of locomotor coordination, such as gait symmetry, in chronic stroke patients were found. All other studies investigating effects of interventions on gait coordination were non randomised designs. Despite restricting the review to include only studies which examined task-specific locomotor training interventions, there was a high degree of heterogeneity amongst interventions and control comparison conditions. Similarly, there was a high degree of heterogeneity amongst measures of gait coordination. Despite the fact that all studies, except one (Ford et al. 2007b), reported measures of either temporal or spatial gait symmetry; each study calculated these measures differently. Given the heterogeneity in measures, interventions and study designs and the number of non-randomised studies deemed to be at high risk of bias the review is limited to a narrative one.

In summary this review has identified that the majority of studies investigating the effects of intervention on gait coordination employ augmentations to TT or OG training paradigms. The type of variations on TT and OG training are many. There was insufficient homogeneity of high quality evidence to determine if task specific locomotor practice interventions are effective in improving aspects of gait coordination. This underscores the fact that there is a dearth of efficacious interventions that specifically target and measure restoration of coordinated gait components (Daly et al. 2006).

Evidence for the effectiveness of locomotor practice interventions on locomotor coordination

Five out of six studies, examining temporal symmetry indices reported significant improvements with the experimental treatment compared to that achieved in the control condition or when comparing pre-post training values. Four of six studies (Waagfjord et al. 1990; Reisman et al. 2007; Roerdink et al. 2007; Westlake and Patten 2009) reported improved step length symmetry with experimental treatment compared to either control treatment conditions or in pre-post training comparisons. Given that the only study to not find improvements in temporal symmetry is the only study to not employ a variation of TT as the experimental treatment; these findings provide support for the effectiveness of TT on temporal symmetry of gait. This is underscored by the fact that the study which directly compared TT to OG walking (Harris-Love et al. 2001) showed TT to significantly improve all temporal aspects of gait parameters compared to OG walking. However, the outcome of Harris-Love and colleagues non-randomised study has not been supported by full RCTs which report contradictory effects of TT on gait parameters (Moseley et al. 2005).

Four of six studies reporting SSWS reported significant improvements in this measure with the experimental treatment compared to that achieved in the control condition or when comparing pre-post training values. Only one of two studies (Plummer et al. 2007) reported improvements in FM scores from pre to post BWSTT + OG training in all but one participant. While the pilot RCT by Westlake et al, (2009) reported significant improvements in BBS scores from pre to post test within *both* control and experimental treatment groups this was not found in the full RCT by Hornby et al, (2008). Plummer et al, (2007) reported improved BBS scores for all participants following BWSTT +OG treatment compared to baseline scores. Only one study (Lindquist et al. 2007) reporting significantly increased SSWS also

reported significant improvements in measures of gait symmetry. Similarly, the study by Plummer et al (2007) reported improvements in all overall measures of gait capacity (SSWS), balance (BBS) and motor impairment (FM) but no concurrent consistent effects of the experimental treatment on symmetry.

Research in healthy adults shows that counter-rotation between pelvis and thorax decreases angular momentum during walking (Wagenaar and Beek 1992). A stroke-related reduction in transverse thoracic rotation can reduce pelvic rotation, stride length and walking velocity (LaFiandra et al. 2003; Ford et al. 2007b). Results from the study by Ford and colleagues (2007) indicated that moving the arms to an auditory rhythm did coincide with improved coordination indicated by increased mean relative phase between transverse thoracic and pelvic rotation which was credited with causing increased stride length. However, the authors did not directly measure stride length and measures preclude clarification if this result is caused by rehabilitation of paretic side or increased compensation by the non-paretic side of the body. Establishing the mechanism by which functional gains are achieved is important in order to improve the design of rehabilitation techniques and functional outcomes (Kautz et al. 2005).

Reisman and colleagues (2007) reported that the phase relationship between legs and hence symmetry of walking changed significantly during split-belt walking. The new phase relationship persisted after exposure to the split-belt paradigm. This result was seen in both individuals with stroke and healthy control participants and led the authors to conclude that participants with stroke appear to use the same means for adapting interlimb coordination as control subjects. The results of this study provide some demonstration that participants with stroke were not impaired in their ability to make immediate adaptations to the locomotor pattern. Importantly, stroke participants were able to alter the locomotor pattern to become

more comparable to that of healthy counterparts despite a compromised neuro-muscular system.

Interventions addressing locomotor coordination deficits

One of the aims of this review was to identify the range of interventions adjunct to locomotor practice paradigms specifically aimed at improving the coordination of walking and turning. This will indicate what treatments currently exist and the theoretical basis on which they are derived and identify where gaps in either theoretical basis or intervention design exist. Task specific locomotor practice, such as repetition of OG walking or treadmill walking, is thought to improve locomotor coordination by stimulating reorganization in the CNS and thereby improve lower-limb motor control and gait patterning (Patterson et al. 2008b). In line with this hypothesis all the studies included in this review employed interventions which were augmentations to either TT or OG task-specific practice.

All studies except for two (Waagfjord et al. 1990; Harris-Love et al. 2001) employed interventions which were augmentations to basic TT or OG locomotor training in an aim to effect gait coordination. Intervention augmentations include auditory cueing (Ford et al. 2007b; Roerdink et al. 2007), BWS (Chen et al. 2005a), BWS +FES (Lindquist et al. 2007), BWS +OG (Plummer et al. 2007), robot assisted TT (Hornby et al. 2008; Westlake and Patten 2009) split belt TT (Reisman et al. 2007) and dual task walking (Yang et al. 2007). Control comparisons ranged from pre-post comparisons (Waagfjord et al. 1990; Plummer et al. 2007; Reisman et al. 2007) to free TT (Chen et al. 2005a; Roerdink et al. 2007), OG (Harris-Love et al. 2001; Yang et al. 2007), therapist assisted TT (Hornby et al. 2008; Westlake and Patten 2009) and stepping to an auditory cue (Ford et al. 2007a).

All studies apart from one (Yang et al. 2007)employed a TT intervention, or variation there-of. The use of TT interventions is based on the theory that movement of the treadmill belt beneath the paretic limb may drive the locomotor system in a more biophysically desirable manner and hence optimize the sensorimotor experience of walking at the spinal and supraspinal levels causing neuro-plastic changes and motor learning (Harris-Love et al. 2001; Lindquist et al. 2007; Plummer et al. 2007). For example, as the TM belt moves the nonparetic limb posteriorally during stance, the center of mass is displaced anterior to the base of support, imposing; appropriate timing of swing and then support from the paretic limb to avoid falling (Harris-Love et al. 2001). Movement of the belt posteriorly during stance also promotes hip extension offering a proprioceptive cue for initiation of swing used to activate and modulate acitivity of central pattern generators (Andersson 1983). Variations to TT, such as BWS, auditory cueing & FES, are typically based on attempts to further augment the normative sensorimotor experience of walking imposed by the treadmill and stimulate neuroplasticity with the hope that this will correlate with changes in motor control. However, evidence for the effect of TT on coordination of gait components is equivocal with RCTs reporting mixed results on these measures (Moseley et al. 2005) therefore, the precise mechanisms by which regular, self supported, TM or OG training could lead to improvements in lower-extremity motor function in chronic stroke patients remain unclear (Harris-Love et al. 2001). Overall there is a lack of emphasis and examination of the transfer of stepping skills obtained in the treadmill environment to the overground domain and inclusion of tasks to develop the ability to adapt to the environment and one’s behavioral goals (Plummer et al. 2007).The rational for different treatment approaches is still weak and needs a better understanding of the 'nature' of coordination deficits in functional tasks after stroke (Van Peppen et al. 2004).

Evidence for improvement of walking performance through rehabilitation of coordination impairments

The mechanism by which improvements in temporal and spatial coordination of gait parameters may be achieved is documented in relatively few of the included studies. Establishing the mechanism by which functional gains are achieved is important in order to improve the design of rehabilitation techniques and functional outcomes (Kautz et al. 2005). For example, Roerdink et al, (2007) found improved temporal symmetry in the auditory paced condition compared to no pacing. This effect may have been achieved by significantly decreased step time on the paretic side. However, whether or not this represents a restitution of impaired leg function in terms of speed of paretic swing or increased compensatory patterns by increased reliance on the non-paretic limb stance is unknown without reported measures of swing and stance phases for each limb. Only three studies were able to provide quantitative evidence for the rehabilitation of paretic limb coordination in the gait cycle. Chen and colleagues (2005) reported a significant reduction in swing time asymmetry in harness support condition compared to free TT. This result was thought to be the effect of BWS allowing increased swing time in the *non-paretic* limb, which can be interpreted as a restitution of paretic limb function in prolonging the weight bearing phase on this limb. Harris-Love et al, (2001) also found single limb support time was significantly increased on the paretic limb and decreased on the non-paretic limb in the treadmill condition compared to the overground walking condition. Waajford et al, (1990) reported increased step length on the non-paretic limb (allowing longer stance time on the paretic limb) causing improved step-length symmetry following TT compared to pre-training

Especially striking in the study of split belt treadmill walking by Reisman and colleagues (2007) is the lack of relationship between fast walking speed and the ability to

make motor adaptations. Previous work has suggested that walking speed in stroke is correlated with level of motor impairment (Brandstater 1983). However, Reisman and colleagues (2007), result that stroke subjects could temporarily store new inter-limb phase relationships and improve symmetry after exposure to split belt treadmill walking, demonstrates that the compromised nervous system is still capable of adapting the locomotor pattern. Furthermore, these results were not correlated with either the level of motor impairment or walking speed. Similar to findings that functional walking ability can be recovered without concurrent recovery in muscle activation patterns (Den Otter et al. 2006; Verheyden et al. 2007; Buurke et al. 2008), this is another example illustrating patients are able to walk at fast speeds, but continue to have underlying locomotor coordination deficits. This makes the utility of this type of split-belt training appealing, as it may be useful in inducing adaptations to the locomotor patterns across a spectrum of patients from slow walkers to fast walkers who continue to have underlying coordination impairments (Reisman et al. 2007).

Overall completeness and applicability of evidence

The evidence is currently insufficient to answer the review questions: What types of interventions are used in adjunct to locomotor practice paradigms in order to specifically target the coordination of walking and turning? What is the effectiveness of task-specific locomotor training interventions in improving coordination of axial segments and lower limbs following stroke?

All but one study reported measures of gait symmetry however; many methods of calculation were unique to individual studies. Moreover, all studies employed different control comparisons, some pre-post test designs and where there were experimental

treatments versus control treatments the type, duration and intensity of these varied between each study. Due to heterogeneity of studies and poor methodological quality of experimental designs a meta-analysis of data was contraindicated.

All of the included studies had inclusion criteria specifying either minimum or maximum levels of walking ability and preservation of at least some cognitive abilities. Therefore, the results of this review may not be generalisable to the wider population of stroke patients.

The lack of sufficient high quality evidence makes it inappropriate to draw conclusions from the results regarding the applicability of locomotor practice interventions to ameliorate locomotor coordination deficits in treatment of chronic stroke patients.

Quality of the evidence

The quality of all but two RCT studies and a pilot RCT included in this review was poor. Study designs left all non-randomised studies open to a high risk of selection, detection, performance and reporting bias. However, most of the included non-randomised studies utilised experimental designs in which participants acted as their own control facilitating equality of characteristics between comparison groups. Few studies randomised order of experimental conditions to minimise selection bias and therefore the majority of studies were open to carry-over effects when comparing pre and post comparisons. Outcome measures were taken using objective measurement devices to quantify locomotor coordination in order to counter detection bias incurred when assessors are not blind to allocation. However, none of the non-randomised studies employed pre-determined protocols and none were able to blind either therapists/researchers or participants allowing all studies to be at risk of performance and reporting bias.

Randomised studies were also not of sufficiently high quality. All utilised concealed randomisation but did not blind outcome assessors to allocation. Only one study (Hornby et al. 2008) reported lost data at follow up and groups in all randomised studies were similar at baseline but only data from participants who completed training were analysed. The control group in the study by Yang and colleagues (2007) did not receive any rehabilitation and therefore groups were not treated equally.

The overall quality of the studies limits confidence in results and therefore meta-analyses were not undertaken as the results could be deemed invalid.

Potential biases in the review process

Through a thorough searching process there is a high degree of confidence that all relevant published studies would have been identified. However, it must be acknowledged that there is a small possibility that there are additional studies (published and unpublished) that were not identified.

Studies involving a single evaluation session were included in this review. It is questionable if these studies constitute intervention studies or merely a test of performance. However, one of the aims of this study was to identify different treatments which could be used to address locomotor coordination deficits. This includes any experimental manipulations which could be used as interventions, provided the study design yielded evidence for the potential efficacy of the intervention.

The single largest potential bias in the review process may be in the subjective decisions regarding whether the aim of the studies was to address locomotor coordination impairments. Where studies did not explicitly state the objective was to determine the effects on gait coordination, but used terminology, in either the primary or secondary statement of

aims, such as gait pattern or gait kinematics; the aim was confirmed by the presentation of one of the listed potential coordination measures e.g. symmetry, relative phase etc. as a primary or secondary outcome measure.

Conclusions

Implications for clinical practice

This review has identified that there is currently insufficient evidence to make any recommendations about the effect of locomotor training interventions on impairments of gait coordination.

Implications for research

High quality RCTs are required to determine the effect of: TT compared to OG training on improving locomotor coordination impairments in chronic stroke patients. The precise mechanisms by which regular, self supported, TM or OG training could lead to improvements in lower-extremity motor function in chronic stroke patients should be documented using secondary measures (i.e. gait parameters presented for both limbs). Future RCTs should examine the transfer of stepping skills obtained in the treadmill environment to the overground domain using follow-up assessments.

Studies are required to perform sensitivity analyses on the effect of combining measures of gait symmetry calculated in different ways and there is a need for further research to identify optimal methods of calculating symmetry as well as for reflecting other aspects of locomotor coordination for use within future RCTs in this area.

Once the specific question relating to the effectiveness of locomotor practice on gait coordination impairments has been addressed, in RCTs suggested above, studies assessing

effectiveness of adjunct interventions incorporating tasks to develop the ability to adapt to the environment and one's behavioural goals (Plummer et al. 2007) may be considered.

There is an urgent indication for primary research studies to explore the 'nature' of coordination deficits in functional tasks after stroke (Van Peppen et al. 2004) in order to better provide rational for different treatment approaches. In particular few studies included in this review examine coordination of axial segments during walking following stroke and few report gait parameters which could point to mechanisms by which interventions are effective. Establishing the mechanism by which functional gains are achieved is important in order to improve the design of rehabilitation techniques and functional outcomes (Kautz et al. 2005). Future studies should include examination of axial segments and report measures which clarify if results of interventions are caused by rehabilitation of paretic side or increased compensation by the non-paretic side of the body.

Further systematic reviews aimed at addressing the effectiveness of locomotor practice on gait coordination is not recommended at this time.

Summary of findings

- Methodological quality of studies is in general very poor, providing insufficient high quality evidence on which to reach generalisable conclusions
- Limited, narrative examples, suggest that TT may be beneficial for improving locomotor coordination
- There is insufficient evidence to determine if improvements in locomotor performance can be brought about through improvements in locomotor coordination
- Many studies use adjunct interventions to address locomotor coordination impairments. Until such time as the benefits of a single intervention have been

examined it may not be beneficial to investigate the combined effects of locomotor practice plus a task augmentation.

- Good quality RCTs are needed to compare the effects of TT and OG locommotor training on gait coordination in chronic stroke patients.
- There is an urgent indication for primary research studies to explore the 'nature' of coordination deficits in functional tasks after stroke in order to better provide rational for different treatment approaches. These studies should include examination of axial segment coordination and documentation of gait parameters providing evidence for the mechanism of effect (i.e. improvement in impairment or further compensatory patterns). Where possible these studies should include experimental design features including random assignment of conditions and control comparisons to limit risk of bias.

CHAPTER 3: METHODS

This chapter outlines methods, such as, kinematic data collection, participant preparation, data management and the calculations of outcome measures which are common to both experimental studies that follow in subsequent chapters. Any methods, such as experimental procedures, which were specific to individual studies are described in the methods section of the individual study chapters.

Data collection:

Full-body kinematics were measured using the Vicon MX (Oxford Metrics, UK), a computerized, three-dimensional video data acquisition system. The system included 13 charge-coupled device cameras, configured on a 6-m walkway, a PC, and software for collection and initial analysis of the data. As participants walked, the three-dimensional position coordinates of retro-reflective markers placed at anatomical landmarks were recorded at sampling rates of 120 or 250 Hz, exceeding the recommended rate for kinematic data of walking (Winter 1995). Walkways were delineated by a 2m wide strip of darker linoleum running along the longitudinal axis of the gait laboratory with additional 3m walkways diverging at 45-degree angles from the longitudinal axis of the straight path, at the half-way point of the straight path (see Figure 3.1). A capture zone encompassing the 6m straight path and the 3m, 45 degree turn branches were calibrated using a static L frame followed by dynamic calibration with a calibration wand in accordance with specifications (Vicon Motion Systems, 2007). Calibration was accepted if the point accuracy (predicted error in the system) was below 1mm at a distance of 6m. For Study 2, the 180-degree turn was performed within the straight walkway.

Justification of turn paradigms and magnitudes

Turns of 45 and 180 degrees were selected for these studies in order to elucidate kinematic impairments in turning ability for turn magnitudes at the smaller and larger end of a spectrum (between 30 and 180 degrees) which has been previously identified as comprising more than three-quarters of all turns in frequent daily tasks (Sedgman & Iansek 1994).The turn magnitudes also coincide with turns less than 50 degrees in which axial segments are reoriented independently and sequentially and greater than 90 degrees when head and thorax have previously been shown to reorient in a more en-bloc style (McCluskey and Cullen 2007; Anastasopoulos et al. 2009). Examination of these two turn magnitudes will help elucidate if stroke survivors have more difficulty with controlling axial segments according to turn magnitude.

Participants

Sample size estimations

Given the sensitivity and accuracy of 3D motion tracking systems (maximum absolute errors of ± 1mm) (Toro & Farren 2003), in measuring differences in kinematics, a small sample size is sufficient to reveal statistically significant differences in motion patterns of healthy adults. Previous studies (Hollands et al. 2001) employing these measures have revealed statistically significant differences using data from 6 *healthy* adults. The only study to date (Lamontagne et al. 2005) quantifying locomotor coordination patterns of stroke patients has revealed significant differences in coordination with 10 stroke patients. A further study by Lamontagne et al, (2009) examining turning kinematics in participants with stroke employed 8 participants but did not report quantitative analyses permitting sample size calculations. A study by Ng and Hui-Chan (2005) was able to identify statistically significant

correlations between TUG times and kinematic measures of gait performance with a sample size of only 11 stroke and 10 control participants. Accordingly, the sample size for these studies (*n*=14 Study 1 and *n*=18 for Study 2) is doubled over previous reports with healthy adults to accommodate larger variability in stroke patients' motion patterns and is in line with sample sizes of current studies of participants with stroke (Lamontagne et al. 2005; Ng and Hui-Chan 2005; Lamontagne and Fung 2009).

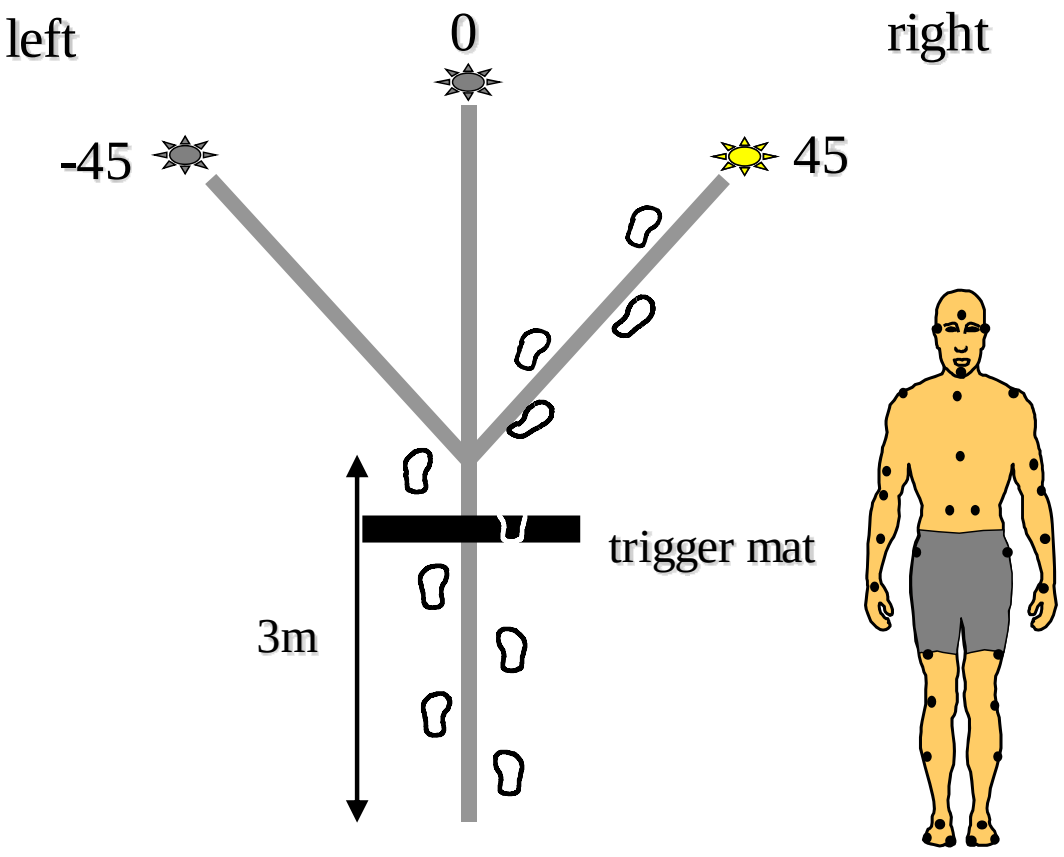

Figure 3.1: Schematic of laboratory set-up and marker placement for 3D motion tracking.

Participant selection

Chronic stroke survivors were chosen as the particular focus of this thesis given that this population has a high incidence of falling during turning, (Hyndman et al. 2002; Andersson et al. 2006) and are 10 times more likely to sustain a hip fracture when they fall than age-matched individuals who have not suffered a stroke (Gustafson 2003). There is mounting evidence that many stroke patients can overcome persistent disability longer than 6 months after stroke (Peurala 2005; Plummer et al. 2007; Patterson et al. 2008b). However, only one fifth of people more than six months after stroke receive rehabilitation to meet their needs (Health 2007; Aziz 2008). Therefore, research is needed to gain an understanding of the specific movement control impairments that may underlie falls incidences during turning in this particular patient group in order to inform the use of rehabilitation efforts beyond the acute stages of recovery.

Participants were, therefore, community dwelling individuals, greater than 6 months post-stroke, recruited from stroke support groups and from participants of previous studies. Control participants were the same gender, within one year of the age of their stroke participant counter-part and were community dwelling individuals recruited from University staff, partners or carers of stroke participants and from participants of previous studies. Ethical approval for the study was granted by the local ethics committee (South Birmingham Research Ethics Committee for study 1 & Black Country Research Ethics Committee for study 2).

Inclusion criteria for stroke patients were;

1) greater than 6 months post stroke and

2) able to walk 10m without assistance or a walking aide

3) gave informed consent.

Both hemiparetic and healthy participants were excluded upon any self report of neuro-muscular (apart from stroke), orthopaedic or rheumatic condition, and visual or perceptual impairment preventing the detection and understanding of visual cues used in the study. They were also excluded if they had receptive and or expressive language problems which precluded a reliable understanding of verbal instructions or giving reliable verbal responses. All age-match control participants scored full marks on the additional clinical measurement scales (detailed below). None of the age-match control participants had a history of falling.

Participant preparation

After reading participant information and signing informed consent form, participants were instrumented with 32 (25mm diameter) reflective markers placed according to the modified Helen Hayes kinematic model (Kabada 1989), bilaterally on the following anatomical landmarks: temples, chin, forehead, C7, A/C joints, mid-upper arm, lateral epicondyles, mid-forearm, wrists, sternal notch, xyphoid process, ASIS, mid thigh, lateral fibular head, mid calves, lateral malleoli, base of the 1st metatarsal and the calcanei (see Figure 3.1). In order to be fitted with these markers participants were asked to wear shorts, t-shirts and trainers. Individual participant measurements (elbow width, knee width, ankle width and weight) to be entered into the Plug-in-Gait (PiG) modelling software (Vicon, Oxford metrics, Ltd) were also taken by adding additional markers to the medical epicondyles, medial border of the knee, and medial malleoli) and capturing a 30s quiet standing trial in which the participant was standing on a Kistler force platform (Kistler Instruments Ltd). Data from the quiet standing trial was exported (in ASCII format) to MS Excel software where subtraction of the mean medio-lateral coordinates of the elbow, knee and ankle markers permitted calculation of elbow, knee and ankle width. Weight was

calculated as the mean of the vertical force component over the 30second standing trial multiplied by 9.8m/s2 (acceleration due to gravity).

Documentation of stroke participants' recovery

Clinical documentation of stroke participants' current physical status was obtained through medical (GP and/or hospital) records (with participants' consent) and through standardized clinical assessments conducted at the time of participation in the Kinesiology Laboratory at The University of Birmingham. These additional functional measurements and measurements of associated deficits of stroke were made to describe clinical characteristics of the group and include:

- Timed Up and Go: The timed "Up & Go" test (TUG) (Podsiadlo 1991) provides a functional test of turning ability in a standardized everyday task, and is a useful way to measure and contrast turning ability in a sample of stroke survivors and age-match controls. The TUG is a test of functional mobility requiring participants to stand up from a chair, walk 3m, turn around (180º) walk back to the chair and sit down. The time taken to complete the test has been shown to have good test-retest reliability in a number of populations including stroke patients (Podsiadlo 1991; Ng and Hui-Chan 2005) and has been claimed to be a good predictor of falls risk in elderly (Shumway-Cook et al. 2000) and acute stroke patients admitted with first ever stroke (Andersson et al. 2006).
- Nottingham Sensory Assessment (NSA) proprioception section – lower limb position matching task (Lincoln et al. 1998). The NSA measures tactile sensations (light touch, temperature, pinprick, pressure, tactile localization and bilateral simultaneous touch, joint movement, movement direction discrimination and joint position sense, on the

face, trunk, shoulder, elbow, wrist, hand, hip, knee, ankle and foot, on both the affected and non-affected side. Recent findings by (Connell et al. 2008) indicate little can be gained from reporting one figure for the incidence of somatosensory impairment without clarification as to the modality and body area assessed. Therefore, we chose to assess only proprioception of the hip, knee, ankle and foot as proprioceptive sensory function of the lower limb is the most relevant to gait ability.

- Fugl-Meyer Assessment (lower extremity subscale) (Fugl-Meyer et al. 1975) is a widely used scale to evaluate sensory and motor recovery after stroke (Gladstone 2002). It is used for both clinical and research purposes. The Fugl-Meyer includes items of lower extremity function that require progressively more complex movements, measures of speed, coordination, and proprioception. Each item is graded on a three-point scale (0 cannot perform, 1 performs partially, and 2 performs fully) with a maximum score of 34 and a higher score indicative of better motor recovery. Standardized protocols for administration were followed (Fugl-Meyer et al. 1975) (see Appendix VI).
- Berg Balance Scale (BBS) (Berg 1989). Balance was assessed with the Berg Balance Scale, which is a 14-item scale that evaluates balance in various sitting and standing activities. Each item is rated on a 5-point scale (0-4) with a maximum score of 56 and a higher score indicative of better balance abilities. Reliability and validity of the BBS for use with people after stroke have been established (Berg et al, 1995). Due to its wide use, the total score is clinically recognisable and comparable to the literature and encompasses aspects of turning ability specifically relevant to the focus of this body of work (see Appendix VII).

- Falls history information was obtained using the Falls Events Questionnaire (Stack 1999) (a prescribed list of questions to record details of falls incidences including the 'Location', 'Fall-related activity', 'Perceived cause', 'Landing' and 'Consequences' of every fall) and participants with a falls history were defined as having 1 or more self-reported falls in the past year (see Appendix VIII).

Data management and preparation:

After reconstruction of the raw marker trajectories by the Vicon MX Workstation software (v5.2, Oxford Metrics, England), all trials were visually inspected and gaps in trajectories were automatically interpolated using the 'fill gaps' function in Vicon Workstation. This function employs a cubic spline interpolation at any instances where the markers were out of camera view for five or less frames (0.02s for 250Hz sampling rate or 0.04s for 120Hz sampling rate) during the movement. After PiG upper and lower body models were run, output data (angular displacement profiles of the trunk, head and pelvis in the global reference frame and three-dimensional location of the whole-body Centre of Mass) was exported in ASCII format to Matlab where bespoke analysis programs written by the author (Appendix IX) were run in order to calculate outcome measures. The kinematic data was then dual pass filtered using a second order Butterworth filter with a low-pass cut off frequency of 5Hz in the Matlab programming environment.

Calculation of outcome measures

The following outcome measures were selected for analysis (detailed description of the derivation of each outcome measure follows below):

Centre of Mass and axial segment reorientation: Studies of turning in healthy young adults have reported a robust and stereotyped sequence of axial segment reorientation ("turning synergy") (Grasso et al. 1998; Patla et al. 1999; Hollands et al. 2001; Courtine and Schieppati 2003a; Prévost et al. 2003; Courtine and Schieppati 2004; Hollands et al. 2004). In order to understand the mechanisms of stroke-related impairment in turning the spatial patterns and relative timing of head, thorax and pelvic rotation were examined and compared to that reported in previous literature.

Gait event analyses & turning stepping strategies: Basic gait event measures (phase durations, step width and length) were taken over the total number of steps of all straight walks in order to characterise and contrast basic locomotor function. Stride adjustments have been shown to be an important contributor to the forces driving turning in healthy young adults (Courtine and Schieppati 2003a; Orendurff et al. 2006). As a result turn stepping strategies were selected to compare between groups and previous literature.

Time to turn and number of steps taken to turn: It is possible that participants with stroke-related difficulty with turning, will require more steps/longer time than unimpaired participants to turn (Thigpen et al. 2000; Dite and Temple 2002). As a result, the time to turn and number of steps to turn were taken as additional performance measures quantifying turning ability.

Calculation of Centre of Mass and axial segment joint angles:

Angular displacement profiles of the trunk, head and pelvis in the global reference frame and three-dimensional location of the whole-body Centre of Mass (CoM) were determined using the Plug-in-gait (PiG) model (Vicon, Oxford metrics, Ltd). The PiG model is a fifteen segment model, derived using well recognised and validated (Kabada 1989; Davis

1991) Newington/Hayes marker placement which consists of six lower extremity links, six upper extremity links, two links for the trunk and one for the head. The PiG model uses optimised lower-limb gait analysis which has been shown to produce reliable clinical output measures including joint angles (Charlton et al. 2004; Hingtgen et al. 2006). The upper body model used in PiG, which outputs head, thorax and pelvis angles relative to the global coordinate system and to each other, has also been validated in modelling upper body motion of stroke patients (Hingtgen et al. 2006).

Masses of each segment were calculated as a proportion of the total body mass using anthropometric relationships reported by Dempster (1955) as well as subject specific anthropometric measures (height, weight, knee width, ankle width) recorded by the investigator. The weighted sum of the CoM of each of the fifteen individual segments was then used to compute the 3-D location of the whole body CoM. The use of CoM trajectories and axial segment angles relative to the laboratory/global coordinate system allow meaningful comparison of results to previous turning literature such as, Hollands et al, (2001) and Patla et al, (1999). Gait speed was calculated (in Matlab programming environment) as the mean velocity of the CoM in the plane of progression over a three second period following the point of contact with the trigger mat. This allowed calculation of gait speed over the period of interest for turns and would encapsulate any variability in speed during turning.

Calculation of step width and step length during turning

Gait events were determined using algorithms described by Hreljac and Marshall (2000), who reported average errors of 1.2ms for both heel contact and toe-off. Heel contact was determined as the zero crossings of the rate of change of the vertical component of the heel marker acceleration. Toe-off was determined as the onset of movement (displacement

>0) in the plane of progression coincident with a local maximum of acceleration (zero crossing in the third derivative) in the plane of progression of the toe marker. All gait events detected in this way through algorithms in the Matlab programming environment were confirmed with frame by frame visual inspection of markers viewed in the sagittal plane.

Stance phase duration was calculated as the time between successive ipsi-lateral heel contact and toe-off. Stance phase duration was then subdivided into single and double support phases. Double support phase was calculated as the time between contra-lateral heel contact and ipsilateral toe-off. Single support phase was the time between successive contralateral heel contacts. Swing phase was calculated as the time between toe-off and the subsequent ipsilateral heel contact.

Indices of temporal and spatial symmetry were calculated from measures of phase durations and step width and lengths. Temporal symmetry was calculated as ((paretic swing/paretic stance)/(nonparetic swing/nonparetic stance)). Spatial symmetry was calculated as (non-paretic/paretic step length) (Patterson et al. 2008a).

In previous literature (e.g. (Patla et al. 1999; Hollands et al. 2001)), the stride length has been computed as the linear distance between two successive positions of the malleolus at foot contact in the plane of progression (x-axis). When turning, the distance covered along the x-axis direction decreases proportionally with the angle of the turn, while lateral displacements (y-axis) gradually increase. Consequently, during turning, the stride length presents components on both x- and y-axis, and therefore, cannot be computed as the distance covered along the x-direction. To avoid computational mistakes, step length and width were calculated as the distances between ankle markers relative to the change in direction at each stride (Huxham et al. 2006). However, each participant used a different number of steps in which to complete the turn. For this reason step-width and length during turn trials were

compared only for the 1 transition stride (2 steps between ipsilateral heel contacts) leading into the turns, i.e. the step on the trigger mat (study 1) or the HC immediately preceeding onset of head reorientation (study 2) and the two subsequent steps. Literature examining turning in healthy young adults suggests that turns between 30 and 90 degrees are accomplished in two steps (one prepatory step slowing the forward momentum evidenced by increased breaking components of the ground reaction force (Patla 1991) and a second direction change step (Patla 1991; Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Therefore, it is crucial to examine the two steps following the cue to turn/initiation of the turn in order to compare with previous literature. It is recognised that these steps may represent a completed turn in healthy control participants but not in participants with stroke. For this reason time to complete the turn is also taken as a performance measure as described in the following section.

Time to turn

Heading direction vector was used to provide a measure of the time varying rotation angle of the overall walking trajectory and to calculate the time taken to turn. In order to compare results with previous literature heading direction vector was calculated in the same manner as performed by Courtine et al, (2003). The linear velocity vector of the CoM in the horizontal plane at each frame of the trajectory defined the heading direction, whose rotation angle with respect to the global reference frame was computed as:

HeadingVect = atan(CoMy/CoMx)

CoMx corresponds to the displacement of the CoM in the sagittal plane, i.e. the axis aligned with progression in the anteroposterior plane along the straight walking path, and CoMy to the displacement of the CoM in the frontal (mediolateral) plane. In order to reveal the global

shape of the heading vector trajectory the heading vector was low-pass filtered using a fourth-order Butterworth filter with a 1-Hz low pass cutoff which removed the lateral oscillations of the CoM inherent in walking (Vieilledent et al. 2001) and amplified by compensatory walking patterns of participants with stroke (Chen et al. 2005b). The maximum angular displacement of the heading vector was then determined and used to quantify the maximum amplitude of turn achieved by all participants. The time to complete the turn was calculated as the time from contact with the pressure mat/delivery of the cue to turn (in Study 1) or the time from the initiation of the first axial segment reorientation (in Study 2 when no cue to turn was provided) to the time when the heading vector reached a maximum angular displacement. The number of steps taken to turn was calculated as the number of HC occurring over the time to turn.

Detection of axial segment reorientation onset latencies

The onset of segment yaw reorientation during a turn trial was measured as the point in time of an acceleration reversal (detected as a zero crossing in the third-derivative) which immediately preceded the sustained deviation (at least 25 frames equalling 200ms) of the turn trial data outside of the 3 standard deviation (SD) boundary of the average straight walking parameter. The onset latency detection method is depicted in Figure 3.2.

In determining the onset latency Matlab algorithms were used to detect a reversal in angular acceleration of each segment which immediately preceded the sustained deviation of the angular trajectory outside of the 3SD boundary of the straight walking trials. In order to ease determination of this local maximum or minimum in acceleration the algorithm looked for the corresponding zero crossing in the 3rd derivative. Using the zero crossing in the third derivative to identify the acceleration reversal simply eases the need to determine which thresholds might signify a local minimum or maximum in acceleration. Instead the algorithm

simply searches for two consecutive data points from the 3rd derivative in which the first is <0 and the next data point is >0.

The advantage of using the zero-crossing in the third-derivative immediately preceding the sustained deviation of the segment yaw profile outside of the SD boundaries is that this point is not influenced by the degree of variability in the segment trajectories during straight walking or the speed of segmental rotation when turning. Detecting the onset latency as the time point when the segment trajectory deviates outside of the 2SD bound, as previously done in several studies (Solomon et al. 2006;Lamontagne and Fung 2009) means that if the variability of one segment's trajectories is less than another segment or that one segment rotates out of the straight SD bounds with greater speed than another segment, the onset latencies of both segments may be detected at the same point in time leading to an interpretation of enbloc reorientation.

It is of utmost importance to the study to be certain that the way onset latencies are calculated is indeed valid. In order to determine the extent that this method of determining onset latencies may have affected the results compared to previously published detection methods (e.g. the point in time when the segment angular trajectory deviates outside the 2 SD boundary (Solomon et al, 2006; Lamontagne et al, 2009)) further analyses were undertaken. The onset latencies for the head, thorax and pelvis segments using the 2SD boundary detection method (Solomon et al. 2006; Lamontagne and Fung 2009) were calculated for 10% of the trials (i.e. 5 trials per participant, totalling 150 trials) and compared these to the results of the detection method employing the identification of the acceleration reversal preceding the deviation outside the SD boundaries in the same 150 trials. The results of these two methods were compared in an ANOVA: between subject comparisons of method (acceleration reversal preceding a sustained deviation outside of the 3SD boundary vs. deviation outside the 2SD

boundary) and within-subject comparisons of group i.e. stroke vs. control and segment i.e. head, thorax and pelvis). This analysis revealed no statistical differences between the outcomes of the two detection methods (see Figure 3.3). Further, the onset latencies detected by each method were highly and significantly correlated ($r=.981$, $n=28$, $p<.001$ two-tailed). Given the theoretical arguments in support of the detection method employing the acceleration reversal preceding a sustained deviation outside of the 3SD boundary, this was the method selected for use in studies 1 and 2.

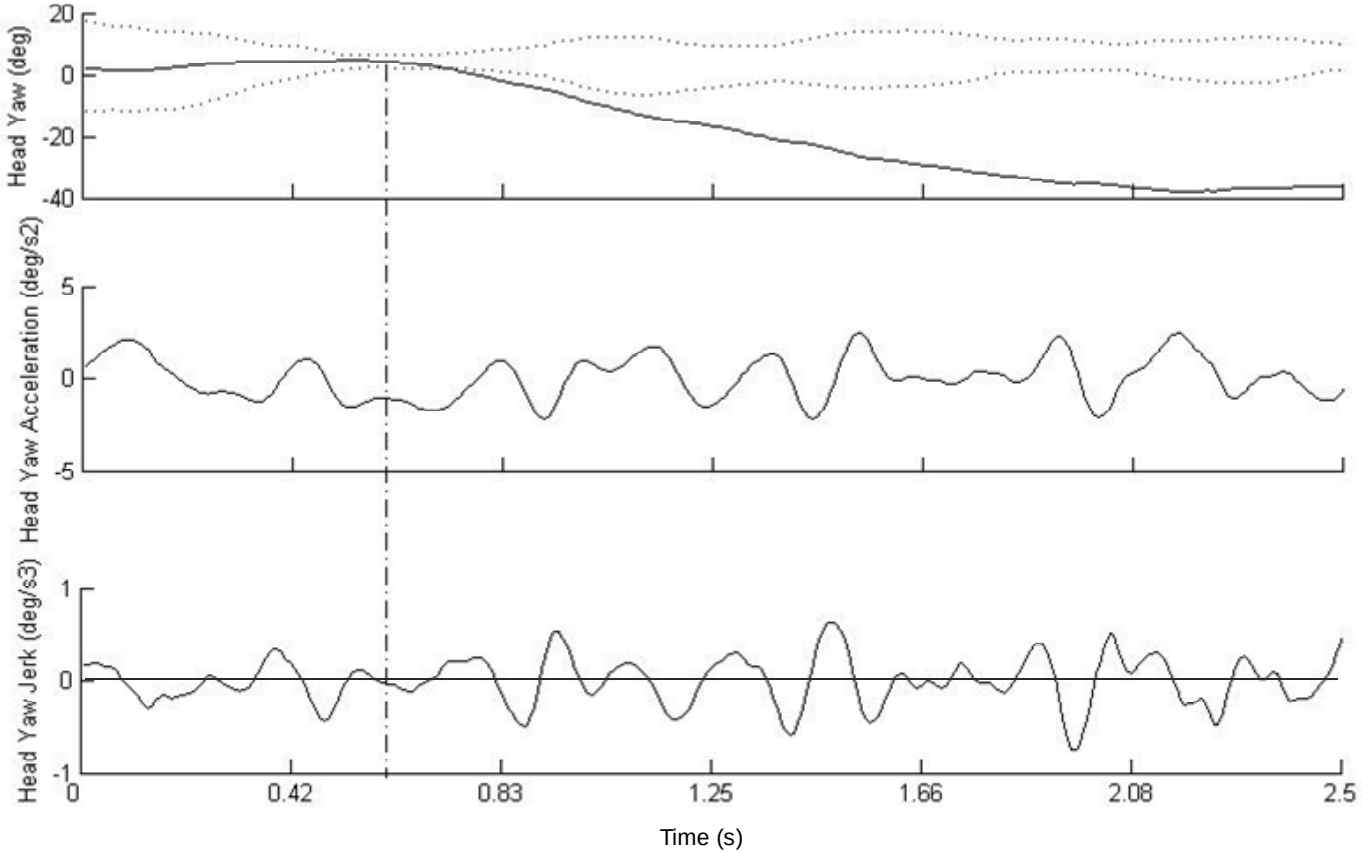

Figure 3.2 Illustration of onset latency detection criterion. Upper panel depicts head angular trajectory for a single turn trial to the left in the LC condition (solid black line) and the 3SD boundaries (dash-dot lines) for the straight walk condition. Middle panel shows the angular acceleration profile for the same turn trial. Lower panel shows the third derivative (Jerk) of head angular trajectory. The dashed line indicates the point at which the onset latency for this trial is determined; as the positive/negative acceleration reversal (identified by a zero-crossing in the third-derivative) immediately preceding the sustained deviation of the head angle outside of the SD boundaries of the straight walks. Time 0 s corresponds to delivery of cue to turn

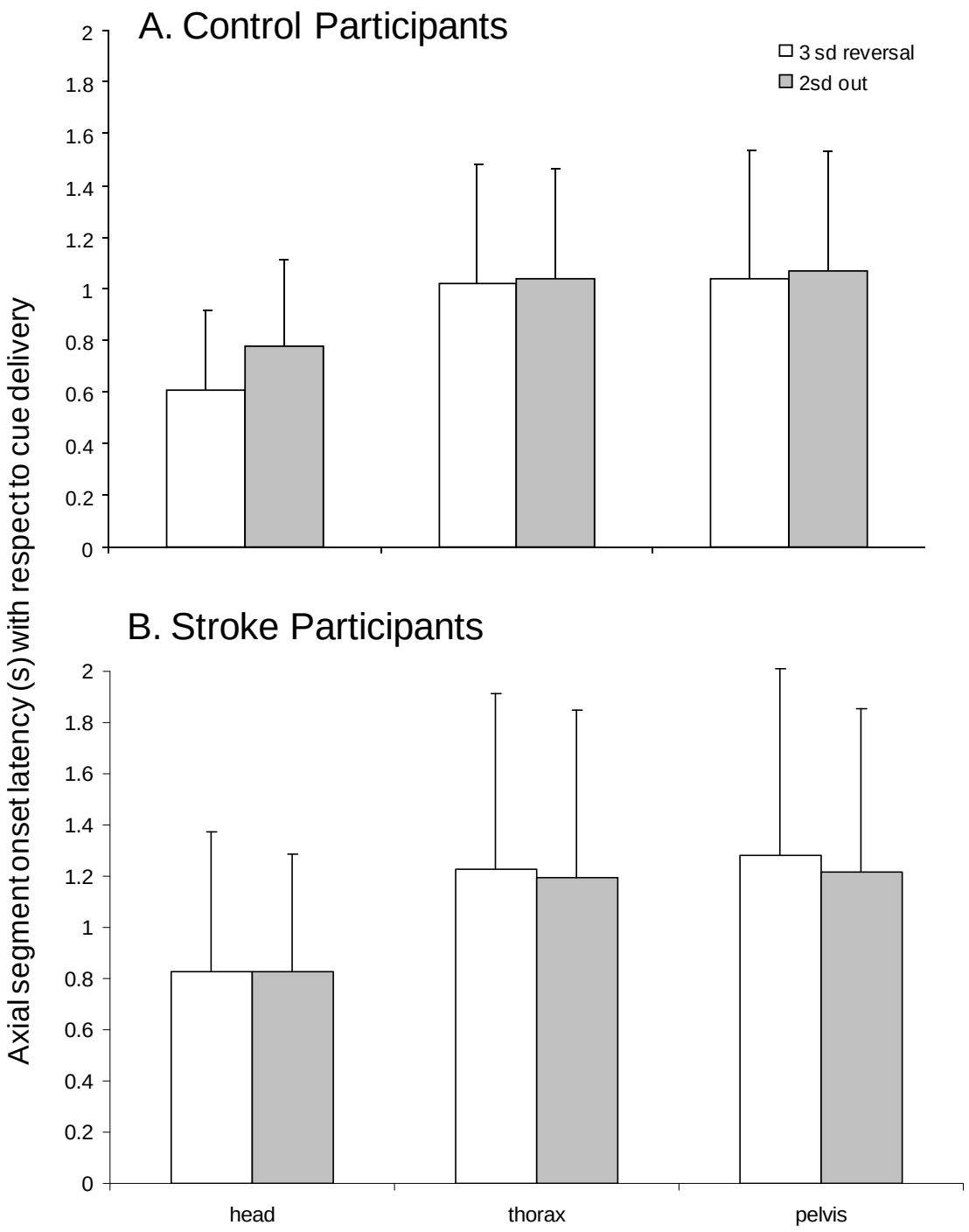

Figure 3.3: Mean latencies for onset of axial segment reorientation to the new direction of travel according to onset latency detection method. Panel A presents group means for control participants. Panel B represents group means for Stroke Participants. 0s coincides with delivery of cue to turn. Unfilled bars represent group means for the detection method using the acceleration reversal immediately preceding the sustained deviation outside of the 3SD boundaries as the criterion. Filled bars represent group means for the detection method using the first deviation outside of the 2SD boundary as the criterion. Error bars are standard deviation.

Controlling for the confound of speed

Some studies (Olney et al. 1998; Barela et al. 2000) have reported walking speed accounts for a proportion of the variance in inter and intra-limb coordination of stroke survivors' walking and that walking velocity has a significant influence on the coordination of axial segments in healthy adults (van Emmerik and Wagenaar 1996). Control participants of Study 1 were asked to perform the direction change task at the same walking speed as their stroke participant counterpart. This additional control for the confound of speed was not possible in Study 2 when the speed of performance of the TUG task was in itself a measure. It is unclear which is the best method to control for the confound of speed. It could be argued that comparison of participant groups walking at their self-selected paces is more desirable than comparing one participant group walking at their self-selected pace to another group who has been asked to perform the task at a slower pace to match speeds (and hence kinematics may be altered due to artificial walking speed). Time normalizing kinematic data to percent stride time (Imai et al. 2001) is one way to eliminate the confound of speed while allowing participants to perform the task at their natural pace. However, time normalizing in this way presents additional confounds when comparing gait of stroke survivors with different spatio-temporal properties to healthy counterparts. For these reasons, comparing temporal gait events such as onset latencies as a function of stride duration would be problematic since any differences found in these measures would likely be a function of between-group differences in temporo-spatial stepping characteristics. One study (Prévost et al. 2003) has investigated the effects of varying speed on turning kinematics in healthy young adults. The spatial structure of axial segment reorientation trajectories was unaffected when participants walked at speeds slower than their natural pace. The results of work by Prévost and colleagues (2003), therefore, provide evidence for the validity of comparing turning kinematics between

stroke participants walking at their self-selected pace to control participants who have been asked to walk at speeds slower than their natural pace.

However, walking speed also varied considerably between participants and hence the effect on dependent measures (i.e. axial segment coordination) would vary systematically between participants according to their walking speed. Therefore, a statistical adjustment by way of Analysis of Covariance (described in detail below) was used to account for the variability in dependent measures associated with the range of different speeds participants walked at (van Emmerik and Wagenaar 1996) and the variability associated with the range of different severities of motor impairment (reflected by walking speed) between subjects (Perry et al. 1995). Walking speed was not included as a covariate for gait event measures given that gait speed is adjusted through alterations in step length and phase durations (Bayat 2005); hence producing a confound between gait parameters and walking speed.

Time normalization

Previous studies of straight walking (e.g. (Imai et al. 2001)) have normalized temporal events to stride time. However, converting values to a percent of stride time in the current direction change studies would add additional confounds making data interpretation more difficult. Since stride durations and gait speed are not comparable between stroke survivors and healthy age-match counterparts (Lehmann et al. 1987; Griffin et al. 1995; Barela et al. 2000), then averaging data to a single stride will introduce a systematic group-related bias in timing measures. There is also the issue of stepping asymmetry exhibited by stroke survivors: a stride made using the paretic limb will have different temporo-spatial properties than a stride made using the non-paretic limb speed (Lehmann et al. 1987; Griffin et al. 1995; Barela et al. 2000). For these reasons, comparing onset latencies as a function of stride duration

would be problematic since any differences found in these measures would likely be a function of between-group differences in temporo-spatial stepping characteristics. Furthermore, all of the previous studies that have investigated latency of axial segment reorientation onset in response to triggered visual cues have analysed onset latency in absolute time (e.g. (Patla et al. 1999; Hollands et al. 2001; Lamontagne and Fung 2009) and therefore analysing onset latencies and other temporally based measures of turning kinematics relative to stride duration would make it difficult to draw comparisons between the results of the current study and these previous studies.

All timing measurements, therefore, were made with respect to the moment of contact with the pressure mat/delivery of the cue to turn (in Study 1) or the time from the initiation of the first axial segment reorientation (in Study 2 when no cue to turn was provided). This experimental design made it possible to test whether stroke survivors need more time following cue delivery to initiate a reactive direction change and whether problems in turning performance/ falls history are linked to differences in when and how the turn is initiated during pre-planned turns.

Statistical model

Prior to analysis data were screened for missing measures and errors by the researcher by examining frequencies, means and standard deviations and looking for outliers. When these were present, the trials from which they were drawn were reviewed to ensure that the unusual values were not errors, or from abnormal trials.

Means and SDs were calculated for each participant in each walking condition for all parameters cited above. Analysis of differences in variability of measures was performed on log transformations of variances in order to account for non-normal distributions (identified

from visual inspection of frequency distribution histograms) (Steele and Torrie 1980). Analysis of variance for repeated measures (ANOVA) was used and the model of between and within subject factors is detailed in each experimental chapter. Walking speed was included as a covariate in Analysis of covariance (ANCOVA) analysis of segment onset latencies, maximum turn amplitude and time to maximum turn amplitude. ANCOVA uses regression to adjust the values of the dependent variable to account for differences that may exist among the groups being studied (i.e. in walking speed) which are not randomly distributed across the groups (Vincent 1999). Use of speed as a covariate in statistical analyses served to remove the variability in dependent measures associated with the non-randomised distribution of walking speeds (van Emmerik and Wagenaar 1996) and to reflect the range of different severities of motor impairment between subjects (Perry et al. 1995). Walking speed was not included as a covariate for gait event measures given that walking speed is adjusted through adjustments in stride length and phase durations; making a confounding link between these variables (Bayat 2005). Post-hoc comparisons were assessed using Bonferroni test with adjustment for multiple comparisons. The software package SPSS (version 15.0) was used. A $P < .05$ was used for statistical significance.

CHAPTER 4: EXAMINATION OF PRE-PLANNED AND REACTIVE TURNS AND THE EFFECT OF LESIONS INVOLVING THE BASAL GANGLIA ON TURNING ABILITY FOLLOWING STROKE

The need for research to explore the time required to turn and the effect of lesions involving the basal ganglia on turning ability post-stroke

Results of the systematic literature review indicated there is an urgent need for primary research studies to explore the 'nature' of coordination deficits in functional tasks, such as turning, after stroke in order to better provide rationale for different treatment approaches. To date there has been very few studies that have examined direction change in persons who have had a stroke. The studies (Lamontagne et al. 2007; Lamontagne and Fung 2009) which have looked at the kinematics of turning in stroke survivors are largely descriptive and only detail reactive turning ability, but suggest impaired coordination of axial segments when turning. However, these studies did not employ quantitative statistical comparisons between participants or participant groups and only explored the kinematics of reactive turns. Evidence that stroke survivors may require more time to adapt straight gait patterns than healthy counterparts (Den Otter et al. 2005) indicates that examination of the role of reactive versus pre-planned turns may be key in understanding potential mechanisms for falls.

The aims of the current study were to extend this work in three ways. Firstly, quantitative analyses of differences between stroke patients and age and gender-matched control participants in measures of gait characteristics, axial segmental coordination, stepping strategies and overall turning ability were performed. Secondly, differences in the ability of stroke patients to alter their walking trajectory in both pre-planned and reactive conditions

were also quantified. Finally, we sought to glean evidence for neural networks which may be involved in controlling turning kinematics by comparing coordination deficits in subgroups of patients with different lesion locations. Given specific evidence for the role of the basal ganglia in controlling axial segment coordination (Mohr et al. 2003; Azulay et al. 2006; Crenna et al. 2007) we sought to examine any differences between participants whose lesions involved the BG and those whose lesions did not. It was predicted that stroke patients would demonstrate an altered sequence and/or timing of axial segmental reorientation and differences in turn-related modifications to step length and width. Differences between groups, in biomechanical measures would be greater when the time available to plan the turn was reduced and we predicted differences between the walking and turning deficits of stroke patients with different lesion locations.

Methods

Participants

Fourteen hemiparetic and gender and age-matched healthy control participants took part in the study.

Table 4.1 details characteristics of stroke participants. Clinical documentation of stroke participants' lesion location and date of stroke was obtained through medical (General Practitioner and/or hospital) records. Standardised tests to describe the motor and sensory deficits were performed by a research physiotherapist (DZ) on all participants and included; Timed Up and Go (Podsiadlo 1991), Nottingham Sensory Assessment (NSA) proprioception section – lower limb position matching task (Lincoln et al. 1998) and the Fugl-Meyer Assessment (lower extremity subscale) (Fugl-Meyer et al. 1975).

Control participants were the same gender, within one year of the age of their stroke participant counter-part and all scored full marks on the Fugl-Meyer Lower Limb and Balance scales and the NSA.

Protocol

A direction change paradigm similar to that used by Hollands et al (2001) was used. This paradigm required participants to walk at their natural self-selected pace along one of 3 walkways; a 6-m straight travel path, or a 6-m travel path with a 45 degree turn right or left at the mid-way point (3m). Participants were visually cued to follow one of these three travel paths either prior to the start of walking (early cue condition (EC)) or at the mid-point of the travel path (late cue condition (LC)). Travel direction was indicated via lights placed at eye-level at the end of each pathway. Light cues were activated when participants stepped on a pressure-sensitive mat placed one-stride length before the midpoint of the straight travel path such that the participant had two steps to plan and implement a direction change in the LC condition. Participants were instructed to start walking with either their left or right leg depending on the required turn direction, so that they were never required to cross one leg in front of the other in order to turn successfully. To ensure that the direction of LC turns were unanticipated, participants were only required to turn during 50% of trials and all trials were randomly ordered. Five trials were collected for each of the four turn conditions (45° left EC, 45° left LC, 45° right EC, 45° right LC) along with five trials for each straight path condition (starting walk with left leg, LC and EC conditions and starting with right leg, LC and EC conditions). Thus 40 trials were performed in total.

Some studies (Olney et al. 1998; Barela et al. 2000) have reported walking speed accounts for a proportion of the variance in inter and intra-limb coordination of stroke survivors

walking and that walking velocity has a significant influence on the coordination of axial segments in healthy adults (van Emmerik and Wagenaar 1996). Therefore control participants were asked to perform the direction change task at the same walking speed as their stroke participant counterpart. Each stroke participant's average walking velocity was determined using the average centre of mass (CoM) velocity in the plane of progression (CoMx) of 10 straight walking trials over the 3 second period following contact with the trigger mat. The lights were programmed to remain on for the time required to reach the end of the pathway walking at the same speed as the stroke participant. Control participants were instructed to pace their walking speed to arrive at the end of the pathway just as the cue light extinguished. Control participants were given several practice trials to acquire the required walking speed.

Statistical analyses

Means and standard deviations (SD) were calculated for each participant in each walking condition for all parameters cited in the previous methods chapter. Since we wanted to determine the contribution of hemiparesis to stroke-related differences in turning performance, for the purposes of statistical analysis it was necessary to group participant data according to whether they turned to the paretic or non-paretic side. Since there were no significant differences in any outcome measures between left and right turns for our control participants, left and right turn data were collapsed to provide averaged control data for comparison with data obtained from stroke participants and this data assigned to both the control paretic and non-paretic groups. Analysis of variance for repeated measures with one between-subject factor group (stroke or control) and two within-subject factors direction (paretic or non-paretic turns) and cue-condition (LC or EC conditions) was used. Within-subject comparisons of segment (head, thorax, pelvis and CoM M/L) were also made in

addition to the factors above, for segment reorientation onset latencies. When analysing differences between groups in gait characteristics over the straight walking trials, the within-subject factor of direction was changed to lead leg (paretic or non-paretic initiating the walk). This corresponded to the fact that each walk was initiated with the leg ipsilateral to a potentially required turn as described above. Walking speed was included as a covariate in ANCOVA analysis of segment onset latencies, maximum turn amplitude and time to maximum turn amplitude. A Pearson product-moment correlation coefficient was computed to confirm the strength of relationship between walking speed and each axial segment onset latency. The mean (SD) correlation coefficient was -.528(.069) and all correlations were significant at at least the 0.05 level (two-tailed).

Lesion subgroup statistical analyses were performed only for the measure of axial segment onset latencies and done in the same manner as for the entire group with walking velocity as a covariate. The between subject factor was lesion (BG lesion, no BG lesion, BG-controls, no BG-controls). Within subject factors were segment (head, thorax, pelvis and CoM M/L displacement), direction of turn (paretic and non-paretic) and cue-condition (EC and LC conditions).

Effect sizes obtained for axial segment onset latencies in pilot analyses predict a required power of 21 participants per group (Effect size: f = 1.13, Alpha = 0.05, power = 0.95, total sample size = 42, critical t(40) = 2.02, delta = 3.66). However this power calculation was performed using the 2SD out onset latency detection method. Once final data analyses had been performed using the acceleration reversal preceding sustained deviation outside of the SD boundary criterion, statistical significance was achieved with 14 participants and so data collection was stopped.

Results

Participants

The stroke survivors participating in this study presented a range of functional levels as indicated by scores on the Fugl-Meyer lower extremity subsection, and the range in gait speeds and TUG times (see Table 4.1). It has been suggested that walking speeds of 0.4 m/s or less and temporal asymmetry indices of 1.5 or greater indicate restricted capacity for community ambulation and greater motor impairment (Perry et al. 1995; Patterson et al. 2008a). Using these thresholds 7 of the participants with stroke in this study could be classed as moderate to severely affected in terms of community ambulation.

Six of the participants with stroke had MRI-confirmed lesions involving the BG, five participants had MRI-confirmed lesions which did not involve the BG and 3 had no confirmed lesion or CT scan results which were insufficient to confirm BG involvement (indicated by asterisks). Post-hoc analyses were carried out to explore the differences between subgroups of stroke survivors with MRI confirmed BG involvement compared to stroke survivors with MRI confirmed lesions *not* involving the BG and their respective subgroups of healthy age-matched counterparts. One BG participant (S13) had to be excluded from analysis of axial segment coordination due to technical problems associated with occluded pelvis markers. A further two participants (and their agematch counterparts) were excluded from step width and length analyses as malleoli markers were occluded. Finally, one participant (and their agematch counterpart) were excluded from phase duration analysis as one heel marker was occluded.

Table 4.1 Characteristics of Participants: Lesion locations confirmed by medical notes documenting CT and MRI scan results. Scores are provided for clinical indicators of recovery and function including; time to perform the timed up and go (TUG) and scores for the lower limb and balance sections of the Fugl-Meyer and Nottingham Sensory Assessment proprioception section. Higher scores on the Fugl-Meyer and Nottingham Sensory Assessment indicate greater recovery. Average walking speed, temporal and spatial symmetry indices are obtained from the average of ten straight walking trials

Participant	Gender	Age	Time since stroke (mths)	Lesion side	Lesion location	Fugl-Meyer Lower Limb (out of 34)	Fugl-Meyer Balance (out of 14)	Nottingham Sensory Scale: Proprioception (out of 3)	Average Walking Speed (m/s)	Temporal Symmetry Index	Spatial Symmetry Index	TUG (s)
S01	female	67	61	right	basal ganglia, frontal lobe, capsula interna	30	13	3	0.61	1.4	0.9	13.9
S02	male	73	79	left	parietal, precentral gyrus	33	11	3	0.57	1.0	1.6	22.5
S07	male	83	51	left	capsula interna	25	10	3	0.45	1.7	1.1	18.4
S09	male	63	25	right	frontal lobe, temporal lobe, insula, basal ganglia	28	12	2	0.70	1.5	1.0	20.0
S10	male	54	22	right	parietal	33	11	2	0.71	1.0	1.1	19.6
S11	female	40	37	right	basal ganglia	28	10	3	0.50	1.6	0.9	19.4
S12	female	54	52	left	insula, basal ganglia, temporal lobe, frontal lobe	26	11	3	0.80	1.7	0.8	10.8
S13	male	49	29	right	basal ganglia, superior and middle temporal gyrus	25	12	3	0.60	2.7	1.0	16.2
S14	male	61	20	left	no confirmed lesion	29	13	2	1.10	1.1	1.1	12.9
S15	male	69	14	right	parietal	32	13	3	0.99	0.9	1.0	11.3
S16	male	59	38	right	basal ganglia	26	12	3	0.91	1.8	0.9	11.1
S17	male	67	11	right	mid-MCA	29	12	3	0.71	1.0		16.0
S18	male	58	88	right	anterior thalamus & capsula interna	32	12	3	0.79	1.5	1.1	12.5
S19	female	49	60	left	posterior communicating artery-	33	14	3	0.97	1.2	0.9	11.2

Measures of Gait Characteristics During Straight Walking Trials

Table 4.2 details all gait measures for both groups.

Step-width & length

There was a significant main effect of participant group on step width (P=.005, F(1,24)=9.43, *n*=26). Stroke survivors walked with significantly wider steps than age-match counterparts. Step width was not significantly different between steps taken with paretic or non-paretic legs or cue-condition for either group.

There was also a significant main effect of group on step length (P=.005, F(1,24)=9.43). Stroke patients walked with significantly shorter steps than their control counterparts. Step-length was not different between limb or cue-condition for either group. The spatial symmetry index was not different between groups or cue-conditions.

Phase Durations

There was a significant interaction effect between lead limb and participant group on mean stance phase duration (P=.006,F(1,26)=9.4, *n*=28). In contrast to their controls, stroke survivors had significantly shorter stance time when stepping with their paretic limb compared to stepping with their non-paretic limb.

There was also a significant main effect of group (P=.050, F(1,26)=4.23) and an interaction between leading limb and group (P=.045,F(1,26)=4.46) on the duration of single-support phase. In contrast to their controls, stroke survivors had significantly shorter single support phase when stepping with the paretic leg than when stepping with their non-paretic limb.

There was a significant interaction between participant group and limb on swing phase duration (P=.005,F(1,26)=9.4). Participants with stroke spent significantly less time in the

swing phase when stepped with their non-paretic limb than when they stepped with their paretic limb.

There was a significant main effect of participant group on Temporal symmetry (P=.003, F(1,26)=11.2). Stroke participants showed significantly greater temporal asymmetry than controls.

Walking speed

There was a significant main effect of cue condition on mean walking speed (P=.05, F(1,26)=4.2). On average, participants walked significantly slower during the Late Cue condition than during the Early Cue condition.

Table 4.2 Characteristics of straight walking gait pattern between groups: All measures provided are means [standard error]. Table a presents spatial gait parameters. Walking velocity means and standard errors are presented for the LC and EC cue-conditions. Step width and length variability are calculated as the mean SD for all trials and conditions. The mean SDs and standard errors of SDs are presented for straight walks initiated with the paretic (Par) and non-paretic (NonPar) legs. Table b presents temporal gait parameters. All gait phase durations are provided in seconds. Again mean and standard errors of each measure are provided for straight walks initiated with the paretic and non-paretic legs

a

Group	Walking velocity (m/s) LC/EC	Spatial Symmetry Index	Step Width (mm)	Step Width Variability (SD) Par/NonPar	Step Length (mm)	Step Length Variability (SD) Par/NonPar
Stroke	.843[.069] / .821[.063]	1.01[.04]	239.95[9.59]	36.12[6.18] / 42.10[5.80]	481.97 [28.12]	50.24[11.92] / 47.62[7.19]
Control	.937[.070] / .870[.063]	1.01[.04]	184.54[9.59]	51.05[6.18] / 48.49[5.80]	562.87 [28.12]	74.18[11.93] / 59.40[7.19]

b

Group	Temporal Symmetry Index	Total stance Par/NonPar	Single support Par/NonPar	Double support	Swing Par/NonPar
Stroke	1.41[.094]	.868[.042] / .943[.047]	.590[.026] / .674[.034]	.284[.018]	.381[.023] / .312[.015]
Control	1.01[.094]	.980[.042] / .978[.047]	.687[.026] / .696[.034]	.290[.018]	.401[.023] / .408[.015]

Axial segment coordination and overall turning ability

Maximum heading vector amplitude and time to turn

There were no significant within or between-group effects on the maximum heading vector amplitude or the mean time to achieve maximum heading vector amplitude. Mean maximum heading vector amplitude and [SD] was 47.8 deg [4.0] for age-matches and 47.2 deg [5.9] for stroke participants. The mean time and [standard error] to reach maximum heading vector amplitude with respect to cue delivery was 3.15s [0.87] and 3.0s [0.73] for age-matches and stroke participants respectively.

Sequence of Segment Reorientation

Figure 4.1 illustrates raw data from one severely impaired stroke participant, one mildly impaired stroke participant and the age-match control for the mildly impaired stroke participant. The graphs describe segmental rotation in the horizontal plane for one straight walking trial (Figure 4.1A) and one late cue turn trial (Figure 4.1 B). These examples show that although the severely impaired participant took significantly longer to initiate and perform a whole-body reorientation in the new travel direction, the sequence of reorientation onset (red arrows on graph) was preserved: head, trunk, pelvis and COM reorientation onset occur in a discrete sequence. It is noteworthy that the mildly impaired patient's data is indistinguishable from that of his age matched control.

There was a significant main effect of segment ($P<.0001$, $F(3,72)=18.1$) on mean reorientation onset latency. Figure 4.2 shows the mean onset latencies with respect to cue delivery for each segment. The head reorients significantly sooner than all other segments, followed by the thorax and pelvis which were reoriented *enbloc* and finally the CoM M/L was reoriented significantly later than all other segments. On average stroke survivors tended to initiate reorientation of all segments later than their control counterparts regardless of the

turning direction or cue-condition; however, these group differences were not statistically significant. There was a strong trend towards an interaction between group, segment and cue-condition (P=.085, F(3,72)=2.3). This trend indicated participants with stroke tended to reorient the head later in the EC condition than their age-match counterparts (see Figure 4.2).

There was a significant main effect of cue condition (P=.043, F(1,24)=4.6) and a significant interaction between cue condition and segment (P<.0001, F(3,72)=6.2) on reorientation onset latency. In contrast to the other segments, the head was reoriented significantly sooner during the EC condition than during the LC condition.

There was a significant main effect of turn direction on reorientation onset latency (P=.015,F(1,24)=6.8). Participants began to reorient segments significantly sooner when turning to the paretic side than when turning to the non-paretic side.

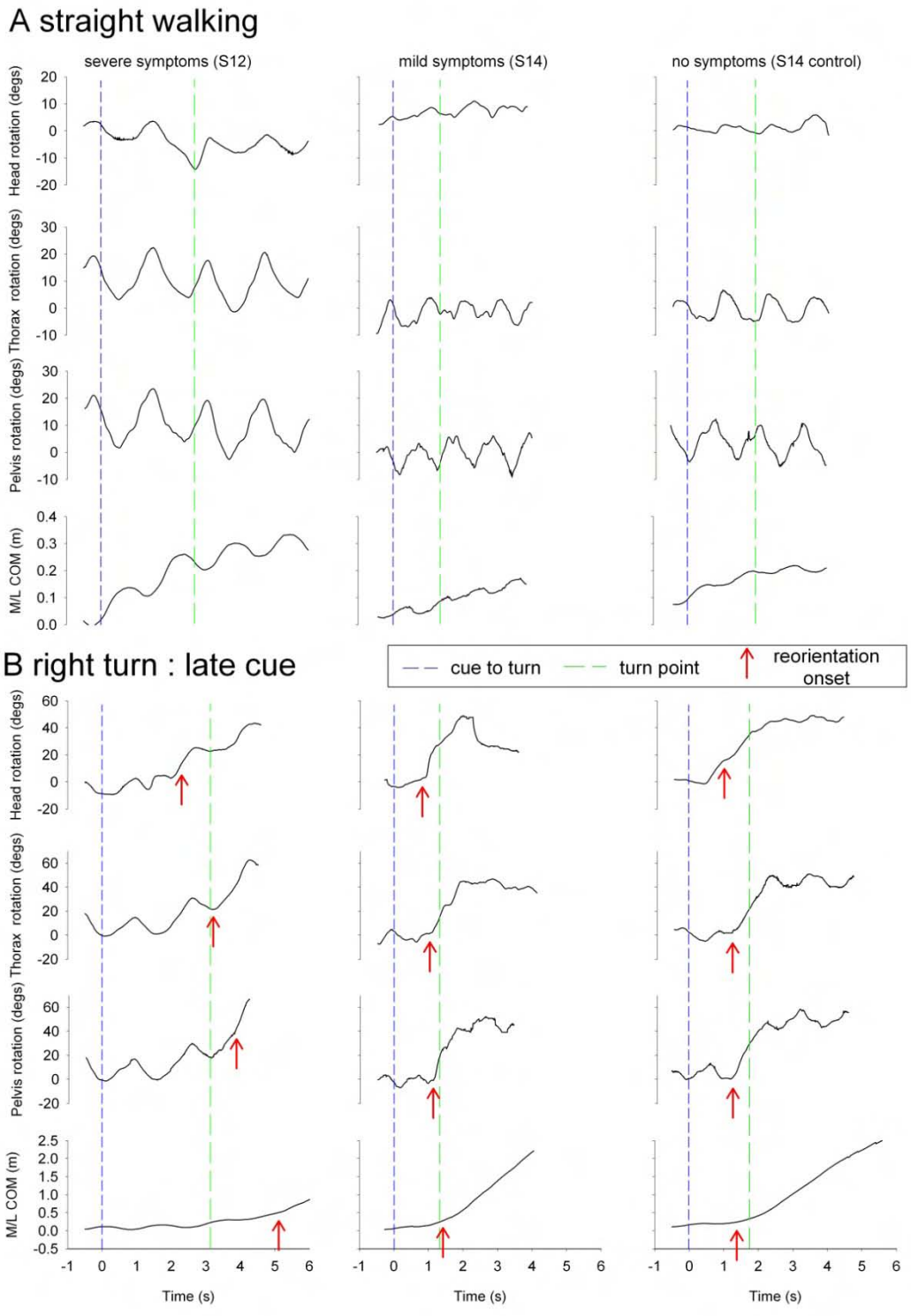

Figure 4.1 Raw segmental horizontal angular displacement obtained data from (1) the most severely affected stroke patient in our sample (S12), (2) the least severely affected stroke patient (S14) and (3) age- and gender-matched control participant for S14. The figure shows data collected during one straight walking trial (a) and one late cue right turn trial (b). The X-axes represent time in seconds with 0 (denoted by line with short dashes) corresponding to contact with the trigger mat two-steps ahead of the turn, i.e. moment of cue delivery. The line with long dashes corresponds to the point that the sternum marker reached the turn point. The arrows show the automatically identified reorientation onset for each segment

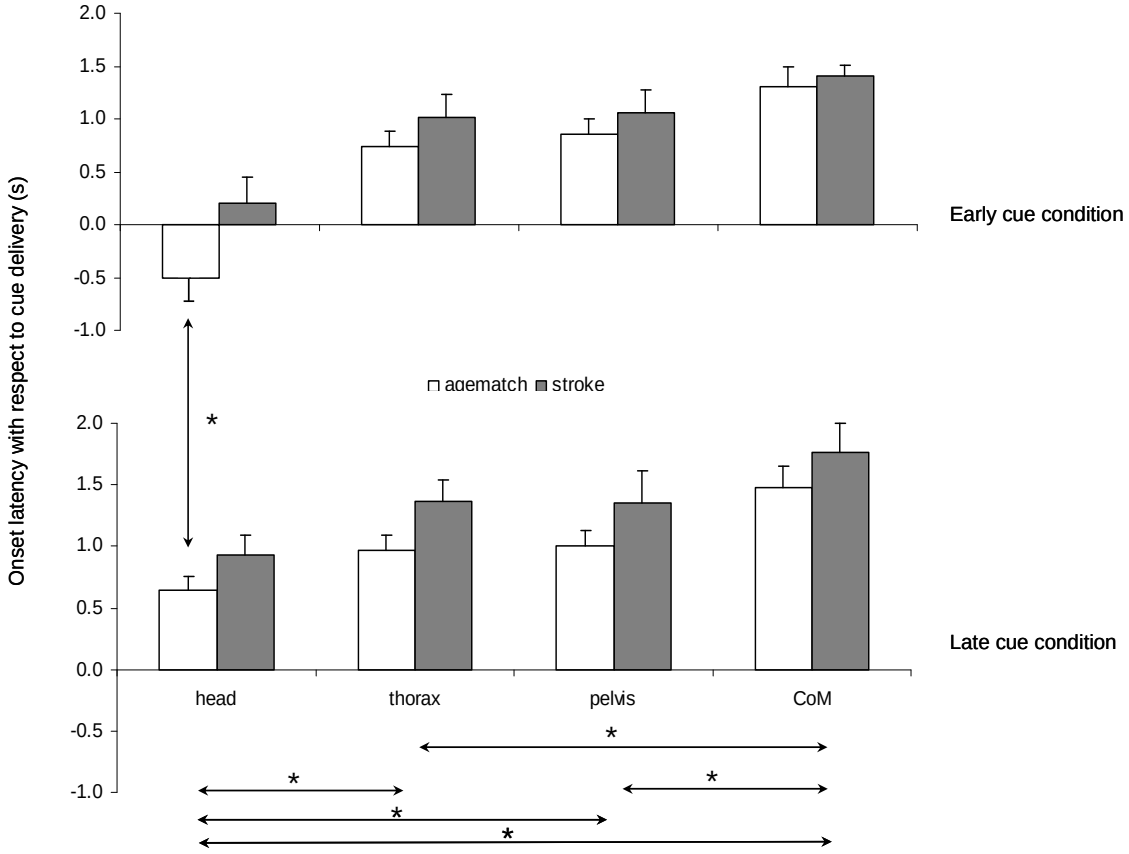

Figure 4.2 Mean onset latencies of reorientation for various segment parameters following a cue to turn and collapsed across turns in both directions. Upper panel depicts mean onset latencies for each segment in the EC condition and lower panel illustrates turns in the LC condition. Unfilled bars represent age-match means, filled bars represent stroke participant means. Bars represent head, trunk, pelvis angles and M/L displacement of CoM, respectively. Error bars indicate standard error. Cue delivery corresponds to time 0 s when the heel contacted the pressure mat two steps prior to the turning point in the pathway

Lesion Sub-Group analysis

There was a significant interaction between lesion group, cue condition and direction (P=.005, F(2,16)=7.6). Figure 4.3 illustrates the mean onset latencies with respect to cue delivery for each segment for lesion subgroups. Post-hoc analysis (one way ANOVA and Bonferroni pair-wise comparisons for each of the four cue conditions) revealed that, on average, BG patients initiated reorientation of their axial body segments significantly later than controls when turning to the non-paretic side. Significant differences between groups are indicated on Figure 4.3.

There were also significant main effects of direction (P=.017,F(1,16)=7.1) and segment (P<.0001, F(3,48)=11.4). These effects indicated stroke participants, regardless of lesion location, initiated turns to the paretic side sooner than non-paretic turns and that all participants utilised the same sequence of axial segment reorientation with the head first, followed by the thorax and pelvis together and then the CoM (Figure 4.3).

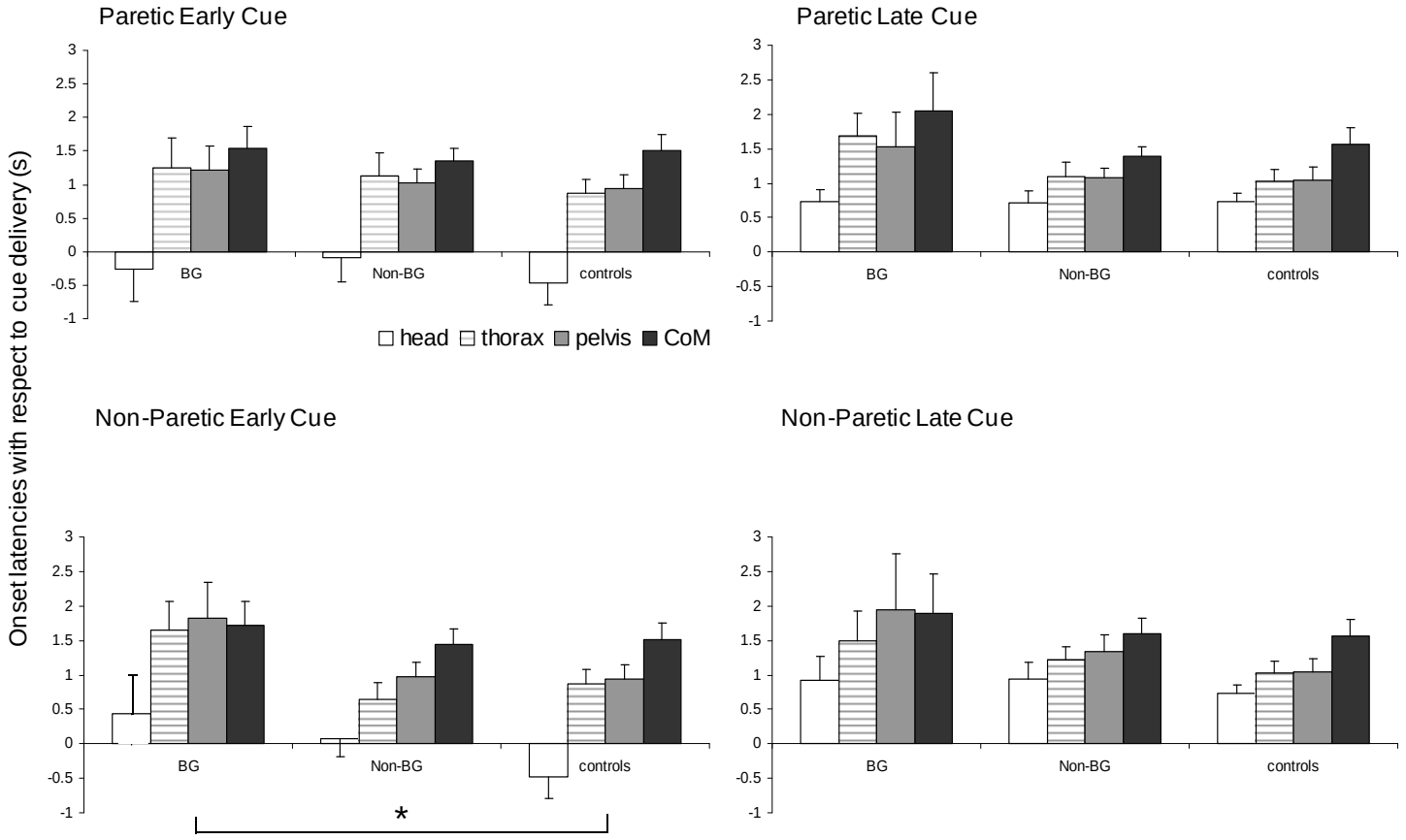

Figure 4.3 Mean onset latencies of reorientation for each segment for subgroup analysis according to lesion and collapsed across turns in both directions. Upper right panel depicts onset latencies for each segment for turns to the paretic side in the LC condition for participants with lesions involving the BG, participants with lesions not involving the BG and age-match counterparts. Upper left panel depicts onset latencies or turns to the paretic side in the EC condition. Lower right panel illustrates onset latencies for turns to the non-paretic side in the LC condition. Lower left panel illustrates onset latencies for turns to the non-paretic side in the EC condition. Bars represent head (unfilled bars), trunk (hatched bars), pelvis (grey filled bars) angles and M/L displacement of CoM (black filled bars), respectively. Error bars indicate standard error. Cue delivery corresponds to time 0 s when the heel contacted the pressure mat two steps prior to the turning point in the pathway

Stepping strategies during the transition stride

Figure 4.4 illustrates step width and length which were measured and compared at 3 discrete times during the turn trials: at the start of the transition stride (contact with the trigger mat corresponding to cue delivery in LC condition) and at each of the subsequent 2 transition steps. There were significant main effects of step (P<.0001, F(2,48)=37.3), group F(P<.0001, F(1,24)=40.44) and turn direction F(P=0.025, F(1,24)=5.7) on step width. There was also a significant interaction between step and group on step width (P= 0.019), F(2, 48) =4.3). On average, the steps of control participants were significantly narrower during step1 compared to the other two transition steps and consistently narrower than those of stroke participants for all steps (Figure 4.4A)

There were also significant main effects of participant group (P=.017, F(1,25)=6.5) and step (P=.001, F(2,50)=8.2) on step length. On average, stroke survivors used shorter step-lengths than their age-match counterparts and the step length of Step 1 was significantly longer than that of Step 2 (Figure 4.4B).

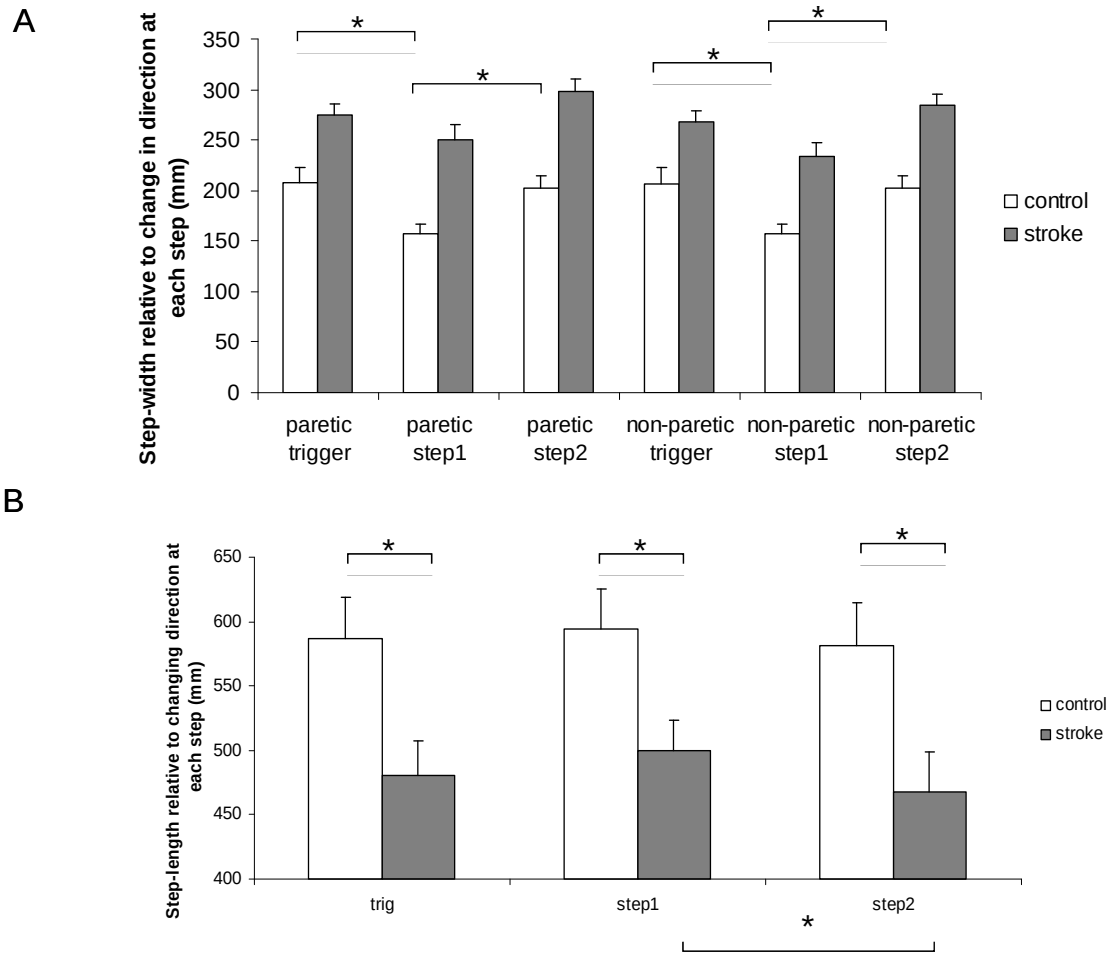

Figure 4.4 Mean step width (upper panel) and step length (lower panel) for each step event during the transition stride (trigger mat step and two subsequent steps) and collapsed across turns in both directions. Unfilled bars represent age-match group means and filled bars represent stroke group means. Error bars represent standard error

Discussion

This is the first study to quantify differences between cohorts of individuals with hemiparetic stroke and age and gender matched counterparts in the kinematics of pre-planned and reactive turns while walking. Contrary to our original hypotheses stroke survivors demonstrated similar stepping strategies, order of axial segment reorientation and ability to achieve the required turn amplitude in the same time frame as healthy age and gender matched counterparts regardless of turn direction or times permitted to plan and execute turns. Analysis of a subgroup of stroke survivors indicated that participants with lesions affecting the basal ganglia took significantly longer than control participants to initiate the reorientation synergy when making turns to their non-paretic side.

Measures of Gait Characteristics

Consistent with previous literature, stroke survivors' basic straight locomotor pattern was found to be characterised by shorter step lengths, wider step widths and shorter swing phase durations (Barela et al. 2000; Kim and Eng 2003). There were no differences seen between groups regarding the time spent in double support phase which is consistent with studies comparing stroke survivors with able-bodied participants walking at similar speeds (Lehmann et al. 1987; Chen et al. 2005b). Stroke survivors were found to be more temporally asymmetric relative to healthy counterparts as indicated by temporal symmetry index but no differences were seen between groups in spatial symmetry. This is consistent with previous findings which indicate that temporal asymmetry is more prevalent than spatial asymmetry in community dwelling stroke survivors who are classified as independent ambulators (Plummer et al. 2007; Patterson et al. 2008a). Despite a moderately severe level of impairment of locomotor ability in half of participants with stroke, these individuals were still able to adapt the straight gait pattern to carry out a turn in much the same way as healthy individuals.

Measures of axial segment coordination and overall turning ability

Stepping strategies during the transition stride

Although participants with stroke used wider step widths and shorter step lengths at each step in the transition stride, they employed the same overall stepping strategy as healthy counterparts. Both groups narrowed the step width of the transition step 1 compared to the trigger mat step preceding it and to the ultimate transition step following it (see Figure 4.4). The narrowing of the base of support in the second step could serve to cut-short the M/L oscillation of the CoM towards the foot to the outside of the required turn (transition step 1) and accelerate the CoM towards the foot to the inside of the turn (transition step 2). The step width of transition step 2 was significantly wider than the step preceding it allowing the CoM to travel further in the M/L direction of the required turn while still remaining within the limits of the base of support. This is contrary to what has been seen in a very similar turning paradigm used by Hollands et al, (2001) in which each of the steps following the trigger mat step were widened. However, step widths at each transition step in this study were approximately 10cm wider than that reported by Hollands and colleagues. The extra width employed by the participants of this study may be associated with the slower walking speed and older average age of participants (Schrager et al. 2008) in this study compared to previous studies.

Both groups were seen to have significantly longer step lengths on the second transition step than on the previous trigger mat step or the proceeding step 2. This step-length strategy contradicts previous reports of step length decreasing in the transition step leading into turns of greater than 30 degrees (Hollands et al. 2001) and decreased step length of the foot ipsilateral to the turn when walking in curved paths (Courtine and Schieppati 2003a).

However, it is unlikely that the 30mm lengthening of transition step 1 over the previous or following steps is functionally significant despite statistical significance. Similarly, despite the fact that participants with stroke stepped significantly wider when turning to the paretic side, the 12mm difference between step widths during the transition stride of turns to the paretic and non-paretic sides is unlikely to be functionally meaningful. One might suggest that the lack of spatial asymmetry in the straight gait patterns of the stroke participants in this study could explain their ability to carry out the turn using an equivalent stepping strategy on both paretic and non-paretic sides. If participants were spatially asymmetric this could facilitate turns in one direction when step lengths and widths need to be asymmetric to achieve a turn and hinder in the other direction when they need to alter the step of the limb which is habitually shorter or wider. However, even the stroke participant with the greatest stepping asymmetry showed only small differences between paretic and non-paretic step widths (4mm) during the transition steps. Therefore, it would seem that persistent impairments in symmetry of straight stepping parameters due to hemiparesis does not impair ability to generate appropriate stepping patterns when turning in either direction.

Sequence of Segment Reorientation

Both groups of participants reoriented their head significantly sooner when the cue to turn was provided at the start of the walk (EC condition) compared to when the cue to turn was provided only 2 steps before the required turn (LC condition). These findings coincide with that of previous work showing that the earlier the cue to turn is provided the sooner the head reorients towards the new direction of travel (Patla et al. 1999; Hollands et al. 2001). While, stroke participants did follow the pattern of reorienting their head significantly sooner in the EC condition than LC condition, there was a strong trend for initiation of head

reorientation to be delayed by approximately 50ms *after* the start of the transition stride, compared to their healthy counterparts who began axial segment reorientation some 500ms *before* the transition stride in the EC condition.

There were no differences between stroke and control participants in initiating the sequence of axial segment reorientation in the LC condition. Although there was a trend towards stroke participants beginning to reorient segments later than their healthy counterparts, this trend was not significant. The preserved capacity of participants with stroke to react and organize the modifications of locomotor strategies to perform the turn with the same success as healthy participants is remarkable. The fact that stroke survivors were able to reorient axial segments in similar times to control participants in the LC condition indicates that physiological changes underlying paresis such as an impoverished ability to activate musculature or decreased force production ability of musculature are unlikely to underlie any impairment. The contrast in stroke survivors' turning abilities between pre-planned and reactive turn conditions indicates potential impairment in the ability to self-initiate a turn (hypothesized to account for similar deficits in turning ability in patients with PD (Vaugoyeau et al. 2006), or a failure to anticipate necessary upcoming changes in the movement pattern in favour of attending to ongoing steps. Indeed results of a dual-task study (Regnaux et al. 2005) showed that stroke survivors' performance of a secondary task was diminished in favour of maintaining characteristics of ongoing steps.

Importantly, the difference in timing of axial segment reorientation of participants with stroke between EC and LC conditions also highlights the potential for visual cues to improve turning ability following stroke. We hypothesize that this improvement is achieved by one of three mechanisms: by externally cueing the required movement and thus overcoming impaired internal cueing of movement sequences, by focusing attention away

from the ongoing step and onto the required upcoming change to the locomotor pattern or, by triggering a gaze redirection which elicits the start of the reorientation sequence. Further studies are required to test these hypotheses before the efficacy of visual cues as a potential intervention to improve turning ability for stroke survivors can be assessed.

Results indicate that participants with stroke were able to reorient segments in the same sequence as healthy individuals and did not do so in an enbloc style. This is a somewhat surprising finding given that a recent study (Lamontagne and Fung 2009) has suggested that a major deficit in locomotion following stroke is the inability to sequentially reorient axial segments to the new direction of travel. However, several important differences between this study and that of Lamontagne et al. (2009) may account for the discrepancy in experimental findings. Firstly, the magnitude of the turn in this study was half that of Lamontagne et al, (2009). While evidence from a previous study (Hollands et al. 2001) indicated that magnitude of turn did not appear to alter axial segment coordination in healthy young adults, more recent studies (McCluskey and Cullen 2007; Anastasopoulos et al. 2009) indicate that standing turns greater than 40 or 50 degrees require more contribution from body rotation and that eye, head and trunk rotations were more enbloc in trials when turns were beyond the visual field (e.g. 90 degrees or greater) and were pre-planned. These findings raise the possibility that adaptations to the basic locomotor pattern required to carry out a 45 degree turn while walking are relatively small and within the abilities of long-term stroke survivors with well established compensatory locomotor patterns to achieve. Secondly, participants of this study were greater than two years post-stroke in contrast to participants of Lamontagne et al.'s (2009) study who were less than one year post-stroke. A recent study by Verheyden et al. (2007) indicated that the coordination of head and trunk may be modified early after stroke but recover over time towards the level of healthy subjects. This finding combined with the discrepancy in results

between the current study and that of Lamontagne et al, (2009) indicates that recovery of axial segment reorientation may occur up to two years post-stroke.

Maximum heading vector amplitude and time to turn

Individuals with stroke were able to complete the turn (defined as when a maximum heading vector angle was reached in the same time (relative to the cue delivery) and achieve the same maximum angular amplitude in the overall heading vector as healthy counter-parts. This indicates stroke survivors did not need more time to carry out either a pre-planned or unanticipated turn in either direction.

Neural basis for control of axial segments during turning while walking

Figure 4.3 illustrates that the subgroup of participants whose lesions involve the BG are significantly slower to initiate the sequence of axial segment reorientation in when turning to the non-paretic side than age-match counterparts. Therefore it would seem that the trend observed in the main analysis for reorientation onset differences between stroke and control participants in the EC condition are driven by differences in the BG sub-group. The BG has been implicated in the control of axial segments during turning (Vaugoyeau et al. 2006; Crenna et al. 2007) and in providing internal cues for the initiation of movement sub-components in well practiced, automatic movement sequences through discharge of activity in the globus pallidus (Georgiou et al. 1993). Recent evidence has indicated that the preferred direction of turning in asymmetric Parkinson's disease patients is ipsilateral to the side of less dopamine activity (Mohr et al. 2003). It is reasonable to assume that a stroke-induced BG lesion would result in altered dopamine activity on the same side of the brain as the lesion (i.e. contralateral to the side of paresis) and therefore a delay in initiating turns to the non-paretic

side would be consistent with an explanation based on asymmetrical activity of dopaminergic pathways. Given that control participants walked at the same speed as their stroke counterparts and that speed was also included as a covariate in analyses, it is unlikely that the trend seen in participants with BG lesion involvement are due to the fact that this subgroup walked at a slower pace or was more severely impaired than the subgroup with no BG involvement.

Conclusions

Contrary to our original hypotheses stroke survivors demonstrated similar stepping strategies, order of axial segment reorientation and ability to achieve the required turn amplitude in the same time frame as healthy age and gender matched counterparts regardless of turn direction or times permitted to plan and execute turns. These results indicate that the locomotor programme is still flexible enough, following stroke, to carry out turns even at short notice; as might be required to avoid an oncoming pedestrian or obstacle. Participants with stroke-induced lesions involving the basal ganglia initiated turns to their non-paretic side significantly later than control participants. This impairment could theoretically promote instability and may help explain the falls epidemiology of community dwelling stroke survivors. These findings highlight the importance of considering lesion location when studying, and attempting to rehabilitate, the movement deficits of individuals who have suffered a stroke.

CHAPTER 5: EXAMINATION OF THE INFLUENCE OF FALLS HISTORY ON TURNING KINEMATICS FOLLOWING STROKE

The need for research examining the link between impaired turning kinematics and falls history following stroke

In the first study to quantify differences between cohorts of individuals with hemiparetic stroke in the kinematics of pre-planned and reactive turns while walking, stroke survivors demonstrated similar stepping strategies, order of axial segment reorientation and ability to achieve the required turn amplitude in the same time frame as healthy age and gender matched counterparts regardless of turn direction or times permitted to plan and execute turns. These results indicate that the locomotor programme is still flexible enough, following stroke, to carry out turns even at short notice; as might be required to avoid an oncoming pedestrian or obstacle. Participants with stroke had a tendency to initiate pre-planned turns to their non-paretic side later than control participants. This impairment could theoretically promote instability and may help explain the falls incidences of community dwelling stroke survivors (Hyndman et al. 2002).

In an attempt to further elucidate potential biomechanical mechanisms which may underlie falls incidences during turning while walking in stroke survivors, a second study was undertaken to examine the kinematics of turning in groups of participants with chronic stroke with and without falls history. Furthermore, in order to extend our current understanding of the 'nature' of coordination deficits during turning while walking, turns of a larger magnitude than used in Study 1 were undertaken in this second study. One study has identified that turns between 30 and 180 degrees comprise more than three-quarters of all turns in frequent daily tasks (Sedgman 1994). Given additional evidence that axial segment

turning synergies are modified for turn magnitudes larger than 50 degrees (McCluskey and Cullen 2007; Anastasopoulos et al. 2009), it is important to determine if stroke survivors are able to adapt axial segment control for larger turn magnitudes which feature heavily in daily tasks.

The primary purpose of this study was to quantify kinematic differences between a sample of community-dwelling chronic stroke survivors and age-matched healthy counterparts in turning coordination during the 180º turn. Secondly, we sought to quantify any differences in turning coordination between sub-groups of participants with stroke with and without a falls history. We predicted that stroke survivors may display indicators of turning difficulty i.e. interrupted or delayed sequence of axial segment reorientation, increased time to turn and/or number of steps to turn and that participants who have had a stroke *and* have a falls history may manifest these difficulties to a significantly larger extent than age-match counterparts or participants with stroke and no falls history.

Methods

Participants

Eighteen participants with stroke, 9 with and 9 without a falls history, volunteered to participate. Table 1 details characteristics of stroke participants. Clinical documentation of stroke participants' side of lesion and date of stroke was obtained through medical (General Practitioner and/or hospital) records. Standardised tests to describe the motor and sensory deficits were performed by a research physiotherapist (DZ) on all participants and included; Nottingham Sensory Assessment (NSA) proprioception section – lower limb position matching task(Lincoln et al. 1998), the Fugl-Meyer Assessment (lower extremity subscale) (Fugl-Meyer et al. 1975) and the Berg Balance Scale (BBS) (Berg 1989). Falls history

information was obtained using the Falls Events Questionnaire (Ashburn et al. 2008) and participants with a falls history were defined as having 1 or more self-reported falls in the past year.

Control participants (*n*=18) were the same gender, within one year of the age of their stroke participant counter-part and all scored full marks on the Fugl-Meyer Lower Limb, Berg Balance scales and the NSA. None of the age-match control participants had a history of falling. Control participants were community dwelling individuals recruited from University staff, partners or carers of stroke participants and from participants of previous studies.

Protocol

Turns performed in the context of the timed "Up & Go" test (TUG) (Podsiadlo 1991) were selected for examination in this study as the TUG provides a functional test of turning ability in a standardized everyday task, and is a useful way to measure and contrast turning ability in a sample of stroke survivors and age-match controls. The TUG is a test of functional mobility requiring participants to stand up from a chair, walk 3m, turn around (180º) walk back to the chair and sit down. The time taken to complete the test has been shown to have good test-retest reliability in a number of populations including stroke patients (Podsiadlo 1991; Ng and Hui-Chan 2005) and has been claimed to be a good predictor of falls risk in elderly (Shumway-Cook et al. 2000) and acute stroke patients admitted with first ever stroke (Andersson et al. 2006).

Participants were asked to perform 20 TUG walks in total, 10 turning towards each of the paretic and non-paretic sides. Direction of the turn within the TUG was verbally instructed prior to the start of the trial. All trials were randomized according to direction of turn-around. The TUG was performed from a chair with arms and seat height adjusted such that each

participant began the sit-to-stand with the knees at 90º of flexion and the forearms resting on the chair arms such that elbows were also positioned at 90º. Participants were instructed to stand up, walk three metres (to a mark on the floor), turn around, walk back and sit down. Participants were asked to perform the task as quickly and safely as they could.

Additional outcome measures:

Head and thorax anticipation distance

Recent studies (Prévost et al. 2003; Sreenivasa et al. 2008) have indicated that head anticipation of the turn occurs at a constant distance from the turn point (~1.1m for turns less than 135º and ~0.9m for 180-degree turns) rather than at a constant time. Thus, in addition to axial segment onset latencies, head and thorax anticipation distance was calculated. The distance from the turn point to the point where the head/thorax started to turn was calculated and named the head and trunk anticipation distance respectively. Distances were computed along the plane of progression of the straight portion of the trial directly preceding the turn. To give an indication of coordination between axial segments in space, maximum head angle around the yaw axis relative to the trunk and the time at which this maximum difference occurred was calculated over the period between 0.5s preceding head reorientation onset and the heading vector turn end (Sreenivasa et al. 2008).

Time to turn and number of steps taken to turn

Time to turn was calculated from the time of initiation of the first segment (head) reorientation to the new direction of travel to the time when the heading direction vector had completed a 180º reversal. The completion of the heading direction vector 180º reversal was determined as the point in time when the heading direction vector angle returned to within

3SDs of the heading angle maintained during the straight walking section of the return walk of the TUG. The SD boundary defining the start of the return walk was calculated in the same manner as to determine axial segment *onset* latencies described in Chapter 3 Methods. The number of steps taken to turn was measured as the number of HCs occurring during the time to turn.

Statistical analyses

Means were calculated for each participant for all parameters cited above. Analysis of variance for repeated measures was used. Comparisons were made between groups with stroke participants subdivided according to falls history and the control cohort divided into two groups to match stroke counterparts. Analyses were therefore completed with one between-subject factor (group: stroke with falls history, stroke without falls history, controls matched to stroke with falls history, controls matched to stroke with no falls history) and within-subject factor (turn direction: paretic or non-paretic side) was used. Within-subject comparisons of segment (head, thorax and pelvis) were also made in addition to the factors above, for segment reorientation onset latencies. TUG time was included as a covariate in ANCOVA analysis of segment onset latencies. This served to remove the variability in this measure associated with the range of different speeds each pair of participants walked at (van Emmerik and Wagenaar 1996) and to reflect the range of different severities of gait impairment between subjects (Perry et al. 1995). TUG time was not included as a covariate for measures of time to turn and number of steps taken to turn given the mechanistic and confounding link between stepping strategies and walking speed (Bayat 2005). Post-hoc comparisons were assessed using Bonferroni test with adjustment for multiple comparisons.

The software package SPSS (version 15.0) was used. A P <.05 was used for statistical significance.

Table 5.1: Participant information

Participant	age (yrs)	time since stroke (mths)	side of paresis	falls history	fall during turning	fall while standing/ sitting	fall while walking	Fugl-Meyer Lower Extremity score (max. score 34)	Nottingham Sensory Assessment (Proprioception subtask) (max. score 3)	Berg Balance Assessment (max score 56)	Berg item: turning to look behind (max. score 4)	Berg item: turning 360deg (max. score 4)	mean TUG time (s)	age-match mean TUG time (s)
S01	62	10	left	none				33	3	56	4	4	25.5	14
S02	49	41	left	none				27	3	54	4	2	49	17
S03	59	50	right	none				25	3	55	3	4	24	16.5
S04	67	73	left	none				32	3	55	4	3	37	19
S05	74	91	right	none				31	3	55	4	4	42	22.5
S06	54	64	right	none				28	3	56	4	4	27.5	17.5
S07	49	72	left	none				33	3	56	4	4	18.5	13.5
S08	63	37	right	none				19	3	56	4	4	40	12
S09	55	6	right	none				32	2	56	4	4	18	17.5
S10	84	10	left	faller	yes	yes	no	31	3	52	4	3	33.5	23
S11	69	26	left	faller	yes	no	yes	26	3	52	4	2	27.5	27.5
S12	60	7	left	faller	no	yes	no	27	2	54	4	3	32.5	15.5
S13	67	7	left	faller	yes	yes	no	23	3	50	2	2	29.5	17.5
S14	40	49	left	faller	no	yes	no	29	2	51	4	2	48	18
S15	58	100	left	faller	no	yes	no	30	3	56	4	4	23.5	19
S16	55	6	right	faller	no	yes	yes	30	3	56	4	4	21.5	16.5
S17	59	7	right	faller	no	no	no	30	3	56	4	4	21	13
S18	55	34	right	faller	no	yes	no	33	3	53	3	3	39.5	19.5

In order to make statistical comparisons between measures of turning ability during turns to stroke patients' paretic and non-paretic sides and that of turns of age-match counterparts to the same direction in space, control participants were nominally assigned to have a "paretic" side which was coincident with the spatial side of paresis in their stroke participant counterpart.

Results

Participants

The stroke survivors participating in this study presented a range of functional levels as indicated by scores on the Fugl-Meyer lower extremity subsection, and the range in TUG times (see Table 5.1). Participants were (mean ± SD) 38.3 ± 31.3 months post-stroke and aged 60 ± 10 years. Participants with stroke who had a falls history had a tendency to have had their strokes more recently (25.2 ± 30.2 months) than those with stroke and no falls history (54.8 ± 25.5 months). Clinical indication of recovery provided by Fugl-Meyer scores was not strikingly different between groups; (mean ±SD) 31±7 for non-fallers and 29 ±3 for fallers. Mean TUG times were similar for the falls group 29.5±9.3s and non-fallers 32.9±10.6s. Berg Balance Scores were also similar between falls 54 ±2.3 and no-falls 55 ±.7 subgroups, however the subgroup with a falls history had more variability on this scale than the no falls cohort.

TUG time, time to turn and number of steps taken to turn

Stroke patients had significantly longer TUG times than age-match counterparts ($P<.001$, $F(3,32)=9.4$). However, there were no differences between participants with stroke according to falls history (fallers vs. non-fallers) or between the two control groups. Furthermore there were no interactions between group and direction of turn or main effects of turn direction (see Figure 5.1).

Time to turn was significantly longer for participants with stroke who had a falls history than for their control subgroup ($P=.010$, $F(3,32)=4.5$) (see Figure 5.2). However, there were no significant differences between participants with stroke with a falls history compared to those without a falls history. There were no differences in time to turn between participants with stroke without falls history and their control counterparts. There were no differences in the time to turn according to the direction of the turn.

The number of steps taken to turn was not significantly different between groups or direction of turn with all groups taking a mean of 2 steps to complete the turn.

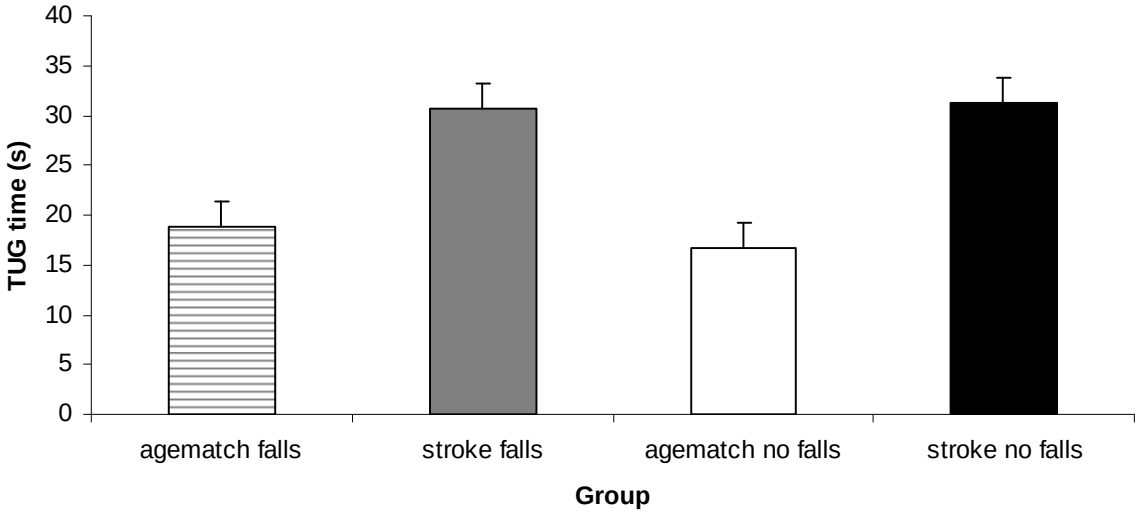

Figure 5.1: TUG time in seconds for each group. Bar with horizontal stripes represents the mean TUG time for the subgroup of control participants who were age-matched to stroke participants with a falls history. Solid grey filled bar represents the mean TUG time for the subgroup of participants with stroke who had a falls history. Clear bar represents the mean TUG time for the subgroup of control participants who were age-matched to the participants with stroke who had no falls history. Black filled bar represents the mean TUG time for the subgroup of stroke participants who had no falls history. Error bars represent the standard error.

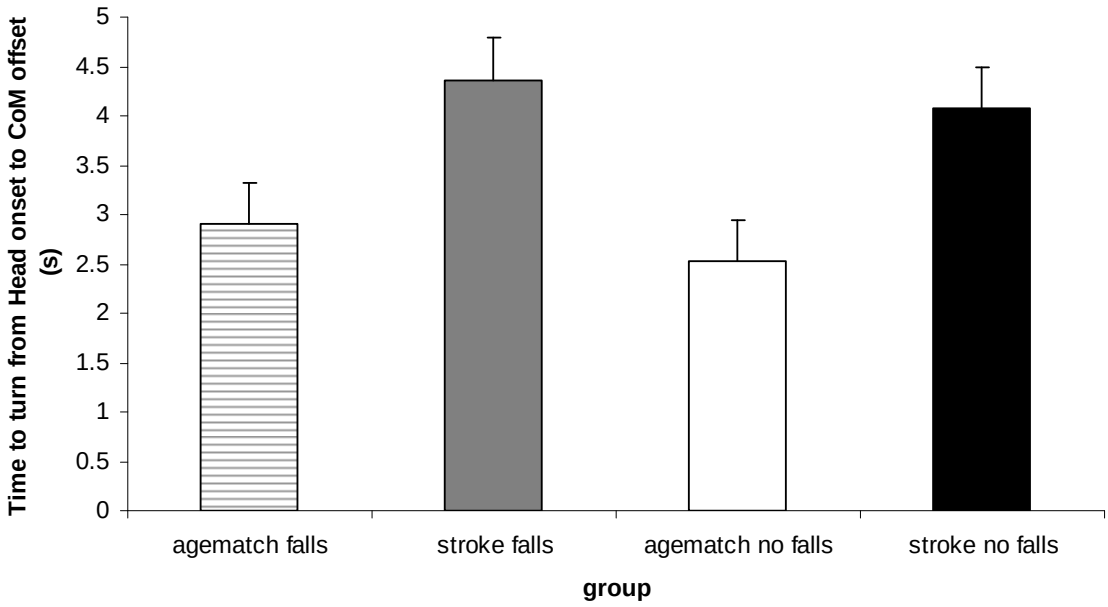

Figure 5.2: Time to turn in seconds for each group. Time to turn is calculated from the onset of head reorientation to the offset of overall heading trajectory. Bar with horizontal stripes represents the mean turn time for the subgroup of control participants who were age-matched to stroke participants with a falls history. Solid grey filled bar represents the mean turn time for the subgroup of participants with stroke who had a falls history. Clear bar represents the mean turn time for the subgroup of control participants who were age-matched to the participants with stroke who had no falls history. Black filled bar represents the mean turn time for the subgroup of stroke participants who had no falls history. Error bars represent the standard error.

Measures of axial segment reorientation

Axial segment onset latencies were not different between groups or direction of turn. From Figure 5.3a it can be seen that the head begins to reorient to the new direction of travel approximately 100-200ms ahead of other axial segments. However, there were no significant differences of onset latencies between head, thorax or pelvis segments for any group.

There was a significant interaction (P=.038, F(3,32)=3.2) between group and direction of turn for the measure of head anticipation distance indicating stroke patients (regardless of falls history) reoriented the head closer to the turn point when turning to the non-paretic side than the paretic side and closer to the turning point than their age-match counterparts (see Figure 5.3b). There were no significant differences between groups or turn directions in the thorax anticipation distance (occurring a mean [SD] of 482.9mm [205.6] ahead of the required turn point for controls and 475.7mm [175.2] for participants with stroke) or in the head anticipation relative to the thorax (head onset anticipating thorax onset by a mean [SD] of 112.4mm [187.6] for controls and 85.6mm [161.4] for participants with stroke). Although a large degree of variability can be seen in these measures, which contributes to non-significant differences, it can be seen that variability is in fact similar between control and stroke participant groups.

The maximum difference between the angle of the head around the yaw axis and the trunk was not different between stroke and age-match counterparts, or according to falls history or direction of turn. The mean [SD] maximum head angle relative to the trunk was 26.8 º [8.35]. This maximum difference of head angle relative to the trunk occurred (mean [SD]) 1.67s [1.06] after participants reached the 3m point where they were requested to turn.

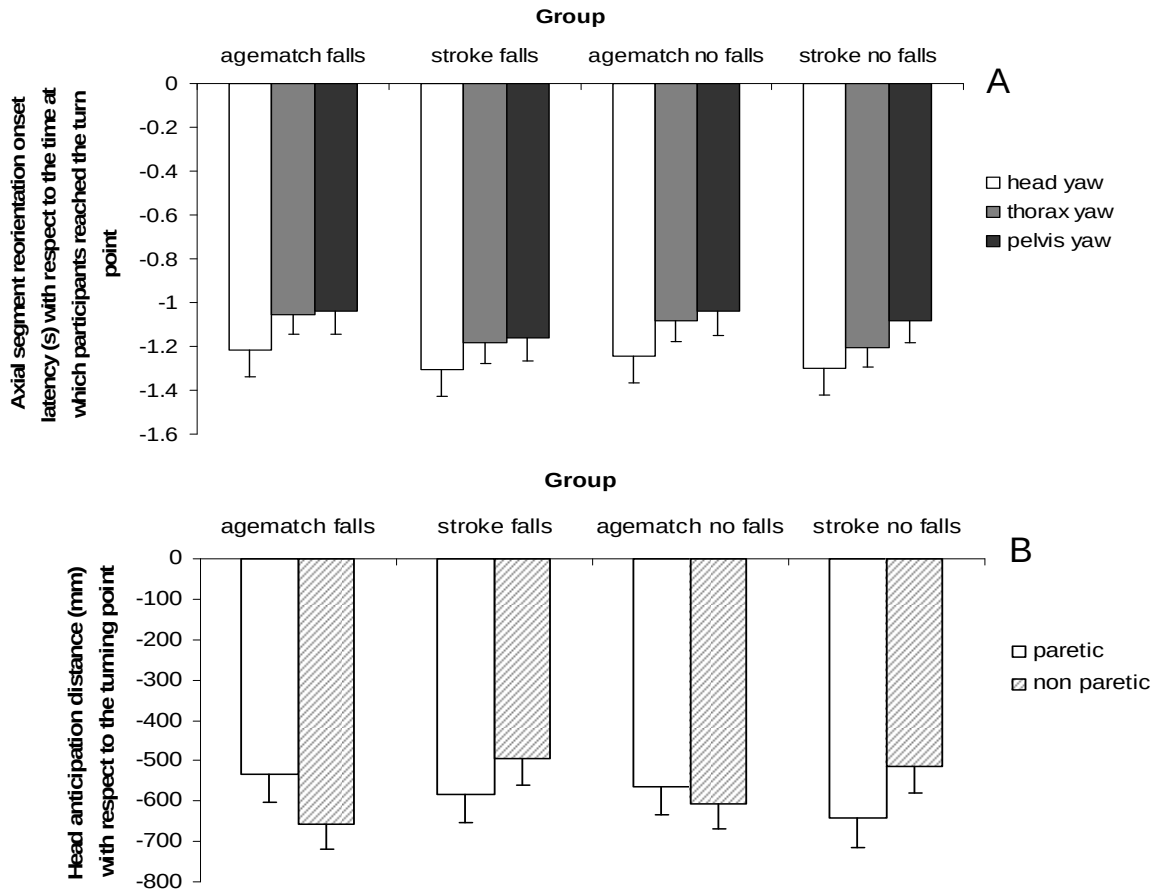

Figure 5.3: Axial segment onset latencies and head anticipation distance by group. Error bars represent standard error. Panel A presents the mean times per group of the onsets of axial segment reorientation with respect to the time at which participants reached the turn point. Time 0 represents the time when the turn point is reached (3m from the chair). Clear bars represent the mean onset latencies for the head yaw reorientation. Grey filled bars represent the mean onset latencies for the thorax yaw reorientation. Black filled bars represent the mean onset latencies for the pelvis yaw reorientation. Panel B represents the distance from the turn point at which the head began to reorient. Distance 0 corresponds to the turning point. Clear bars represent the mean head anticipation distance for turns to the paretic side and the hatched bars represent the mean head anticipation distance for turns to the non-paretic side.

Discussion

This is the first study to examine the kinematics of turning in groups of participants with stroke with and without falls history during the TUG task. Community-dwelling, chronic stroke survivors with and without falls history were able to carry out the 180-degree turn during the TUG task in a very similar manner to age-match healthy counterparts. This is a surprising finding since 50% of community-dwelling stroke survivors fall and a large proportion of those falls occur while turning (Hyndman et al. 2002). Half of our stroke participants had a falls history and half of those reported falling while turning. Although participants who had a stroke and falls history took significantly longer to turn than age-match controls, we found no kinematic differences in performance or in the axial segment coordination during turning which could contribute to falls history or falls risk. Therefore, other explanations for falls epidemiology during turning in individuals living at home, who are greater than 6 months post-stroke(Hyndman et al. 2002), need to be explored. It is likely that deficits in cognitive processes such as attention (Hyndman 2003) or central integration (Plummer-D'Amato et al. 2008) and/or sensory deficits(Connell et al. 2008) are contributory factors.

Stroke survivors in this study did have significantly longer TUG times than their age-match healthy counterparts. The time taken to complete the TUG has been claimed to be a good predictor of elderly and stroke patients at higher risk of falling (Lundin-Olsson 1998; Shumway-Cook et al. 2000; Andersson et al. 2006). However, in this study TUG time was not significantly different between stroke patients with and without falls history. This finding is consistent with those of a recent study (Thrane et al. 2007) which indicated that the TUG has a poor ability to classify fallers in a group of community-dwelling older people. Studies have suggested that TUG times greater than 14(Andersson et al. 2006) or 30s (Podsiadlo 1991)

indicate greater risk of falling. All of the participants with stroke in the current study have TUG times greater than the 14s threshold, but only half of these participants have a history of falling. Similarly, only 4 healthy age-match control participants completed the TUG in 14s or less and none of these participants have a falls history. Half of the stroke participants in this study took longer than 30s to perform the TUG but do not have a falls history. These findings raise doubt over the association of TUG time with falls history in community-dwelling, chronic stroke survivors. It may be that the validity of the TUG to predict falls in acute stroke patients admitted to hospital (Andersson et al. 2006) may decrease in samples of individuals with chronic stroke who have regained independent mobility.

Participants with stroke who had a falls history took significantly longer to turn than controls with no falls history. This confirms previous findings that a longer time to turn may be an indicator of turning difficulty and is associated with an increased risk of falling (Lipsitz et al. 1991; Thigpen et al. 2000; Dite and Temple 2002). Indeed a lower score on the BBS is given for requiring greater than 4s to turn 360º (Berg 1989) and another study indicates longer than three seconds to turn 180º during the TUG is an indicator of difficulty when turning (Thigpen et al. 2000). Participants with stroke who had a falls history in this current study took longer to turn than controls, with a mean turn time of 4.4s. This time exceeds previously identified thresholds (Berg 1989; Thigpen et al. 2000) indicating turning difficulty.

Several studies indicate the use of more steps when turning is thought to signify instability and the loss of coordination (Dite and Temple 2002; Fuller et al. 2007). Suggestions for thresholds of number of steps to turn which indicate falls risk in groups of community-dwelling older adults vary from use of more than 12 steps to complete a 360º turn (Lipsitz et al. 1991) to the use of five or more steps or weight shifts to accomplish a 180º turn and an absence of pivoting during the turn as indicative of turning difficulty (Thigpen et al.

2000). However, the group of participants with stroke and falls history in this current study did not differ in the mean number of steps required to turn 180º during the TUG from the stroke group without falls history or the healthy age-match counterparts. All groups had a mean of 2 steps to complete the turn. Turning with only 2 steps indicates a pivot strategy was used to carry out the turn. It has been previously suggested (Thigpen et al. 2000) that individuals who accomplish a turn using a multiple step strategy as opposed to a pivot strategy may do so to compensate for a lack of ability to carry out the more ballistic feed-forward strategy of pivot turn. Although the group of participants with stroke who volunteered for this study exhibited residual paresis in the lower limb (< 34 on Fugl-Meyer lower extremity scale), they all still employed a pivot turning strategy. However, the fact that longer time to turn was not accompanied by an increased number of steps for participants with stroke is surprising. We hypothesize this result is due to the fact that participants with stroke have longer TUG times than control participants which has been shown to correlate highly(De Bujanda et al. 2003; Ng and Hui-Chan 2005) with slower self-selected gait speed. It seems therefore, that participants with stroke may adopt the same stepping strategy while turning but take longer to carry out the stepping pattern as a result of slower overall gait speed.

Coordinating axial segments for turns of 60º or less studies in healthy individuals, involves sequential reorientation of the head thorax and pelvis to reorient the body to the new direction of travel (Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Recent studies (McCluskey and Cullen 2007; Anastasopoulos et al. 2009) have shown that standing turns greater than 50º require more contribution from body rotation and that eye, head and trunk rotations were more en-bloc in trials when turns were beyond the visual field (e.g. 90º or greater) and were pre-planned. Results of this study corroborate those of more recent studies(McCluskey and Cullen 2007) indicating that turns of 180º are started by initiating

reorientation of axial segments to the new direction of travel within 100-200ms of each other. This is a strategy which was adopted by all participants including those who have had a stroke with and without history of falling. This is a surprising finding given that a recent study (Lamontagne and Fung 2009) has suggested that a major deficit in locomotion following stroke is the inability to sequentially reorient axial segments to the new direction of travel. However, several important differences between this study and that of Lamontagne et al, (2009) may account for the discrepancy in findings. Firstly, the magnitude of the turn in this study was twice that of Lamontagne et al, (2009). Given that recent studies (McCluskey and Cullen 2007; Anastasopoulos et al. 2009) have indicated coordination patterns of axial segments vary according to the magnitude of the turn this may account for differences in results. Secondly, the method of detecting segment reorientation onset latencies may contribute to differences in results. Finally, participants of this study were greater than two years post-stroke in contrast to participants of Lamontagne et al.'s (2009) study who were less than one year post-stroke. A recent study by Verheyden et al, (2007) indicated that the coordination of head and trunk may be modified early after stroke but recover over time towards the level of healthy subjects. This indicates that recovery of axial segment reorientation may occur up to two years post-stroke.

A recent study (Sreenivasa et al. 2008) has indicated that head anticipation of the turn occurs at a constant distance (~1.1m for turns less than 135º and ~0.9m for 180-degree turns) from the turn point rather than at a constant time. In this study all participants were seen to reorient the head approximately 0.5m from the required turn point. An interaction effect indicated that stroke patients (regardless of falls history) reoriented the head closer to the turn point when making turns to the non-paretic side compared to the paretic side. Differences in reorientation of axial segments when turning to the non-paretic side may be due to the effects

of asymmetrical activity of dopamine systems (Mohr et al. 2003). Recent evidence has indicated that the preferred direction of turning is unilateral to the side of less dopamine activity (Mohr et al. 2003). We hypothesize that in participants with stroke less dopamine activity may occur in the lesioned hemisphere and manifest in altered turning behaviours to the non-paretic side, unilateral to the side of the lesion.

Further indication of the coordination between axial segments during turning may be gained by examining the maximum difference between head and thorax angles around the yaw axis. Our results indicate that the maximum head angle relative to the thorax is approximately 27º and occurs 1.7 seconds after the required turning point. These results are in-line with what has previously been reported in healthy participants (Sreenivasa et al. 2008) and indicate that despite the head and thorax beginning to reorient to the new direction of travel at the same time, the head soon rotates beyond the trunk in the direction of the turn. One reason that the head rotation may exceed that of the trunk is to facilitate view of the new travel path for as long as possible when the new walking path is initially out of view (Sreenivasa et al. 2008).

Without any falls-related differences in coordination of turning it is difficult to indicate why individuals with stroke and falls history take longer to turn than control participants or what the mechanism for falls epidemiology in this population might be. Given that participants with stroke and falls history experienced their stroke more recently than those without falls history, it may be that individuals with falls occurring in the subacute stages have experienced further recovery since their falls and hence show little difference in kinematics of turning compared to participants with stroke and no falls history. However, falls early after stroke have been shown to predict falls later after discharge (Forster and Young 1995) so it could be expected that those who fell in the first 6 months following stroke would

be at greater risk for subsequent falls and hence may show kinematic differences in turning ability.

Other studies have indicated many different risk factors for falling in long term community-dwelling stroke survivors and some have found contradictory results for predictors of falls. Individuals are more likely to fall if they have depressive symptoms, residual paresis and epilepsy (Jorgensen et al. 2002) or concurrent motor and sensory impairments (Yates 2002). Other studies have indicated that residual motor impairments were *not* associated with increased risk of falling (Lamb et al. 2003) but that attention deficits and an inability to divide attention (e.g. talking while walking), are correlated with falling (Hyndman 2003; Plummer-D'Amato et al. 2008). The cumulative evidence from these studies combined with the results of this current study indicate that falls occur in long-term community-dwelling stroke survivors due to factors other than impaired ability to coordinate reorientation of axial segments or produce appropriate stepping patterns while turning.

Limitations

It could be argued that the lack of significant differences between fallers and non-fallers in our outcome measures was due to inadequate statistical power due to relatively small participant sample size. The sample size used by Ng and Hui-Chan, (2005) was used as a guideline indicating the sample size required to identify differences in kinematic measures of walking according to falls history. Nevertheless it is possible that differences in turning coordination between fall groups are more subtle than stroke-related changes to step length, width and gait speed. However, the differences between groups in the current study were very small e.g. a maximum of 100ms difference between onset latencies for any of the axial segments. Therefore, even if we had used sufficient sample sizes to show that these very small

differences were statistically significant it would be difficult to assign functional significance to these differences that may explain falls behaviour.

The study is also limited in ecological generalizeability as to the cause for falls in more cluttered/busy environments by the fact that performing a TUG in a lab environment is not representative of the task of turning in the home. The fact that we found no kinematic differences in turning behaviour according to falls history in our sample does indicate that the influences such as trip hazards and distractions to attention should be considered in future studies.

Implications

These results indicate incidences of falls during turning following stroke may not be due to impaired movement patterns alone. On this basis, we suggest that clinical rehabilitation efforts as well as further studies should address the interplay of impaired movement production with the many other factors which are associated with falls in long-term, community-dwelling stroke survivors, such as attention deficits, sensory impairment and depression.

CHAPTER 6: GENERAL DISCUSSION

Summary of findings

Systematic literature review

A systematic review of the literature identified that the majority of the eleven included studies, investigating the effects of locomotor practice interventions on gait coordination are non-randomised research studies (employing augmentations to treadmill (TT) or over-ground (OG) training paradigms. All studies, apart from one (Yang et al. 2007), employed a TT condition, or variation there-of. The type of variations on TT and OG training were unique to each study and included; body-weight support (BWS), auditory cueing, split-belt walking, robot assisted TT and dual task paradigms. The use of TT interventions is based on the theory that movement of the treadmill belt beneath the paretic limb may drive the locomotor system in a more biophysically desirable manner and hence optimize sensorimotor stimulation at the spinal and supraspinal levels causing neuro-plastic changes and motor learning (Harris-Love et al. 2001; Lindquist et al. 2007; Plummer et al. 2007). All the adjuncts to TT training were included in attempt to augment the normative sensori-motor walking patterns already imposed by the treadmill/OG training in order to further stimulate rehabilitation/recovery. Overall there was a lack of follow-up assessments to examine the transfer of stepping skills obtained in the treadmill environment to the OG domain. There was also limited inclusion of tasks to develop the ability to adapt to the environment and different task goals (Plummer et al. 2007). The sparse number of randomised controlled trials included in the review underscores the fact that there is a dearth of efficacious interventions that specifically target and measure restoration of coordinated gait components (Daly et al. 2006).

In the studies that were included, there was insufficient homogeneity of high quality evidence to determine if task specific locomotor practice interventions are effective in improving aspects of gait coordination. All but one study reported measures of gait symmetry however; methods of calculation were unique to individual studies. Moreover, all studies employed different control comparisons, some pre-post test designs, and where there were experimental treatments versus control treatments the type, duration and intensity of these varied between each study. Therefore, results from different study designs were expected to differ systematically, resulting in increased heterogeneity. It was therefore determined that they could not be combined to indicate effectiveness of locomotor practice interventions on gait coordination.

Furthermore, most of the included studies were judged to be of poor or uncertain methodological quality according to the Downs & Black (1998) checklist. All studies were, therefore, judged to be at high risk of bias. Most of the included experimental studies utilised designs in which participants acted as their own control facilitating equality of characteristics between comparison groups. However, only one study (Roerdink et al, 2007) then randomised order of experimental conditions to minimise effects of selection bias and therefore the majority of studies were open to carry-over effects when comparing pre and post comparisons. Outcome measures were taken using objective measurement devices to quantify locomotor coordination in order to counter detection bias incurred when assessors are not blind to allocation. However, none of the studies employed pre-determined protocols and none were able to blind either therapists/researchers or participants allowing all studies to be at risk of performance and reporting bias. Due to heterogeneity of studies and poor methodological quality of experimental designs a meta-analysis of data was contraindicated.

The scarcity of rigorously controlled RCTs examining the effects of locomotor interventions on the restoration of gait coordination may be due to the fact that the rational for different treatment approaches is still weak and there needs to be a better understanding of what constitutes coordination deficits in functional tasks after stroke (Van Peppen et al. 2004). Therefore, there is an urgent indication for primary research studies to explore the characteristics of coordination deficits in functional tasks after stroke in order to better provide rational for different treatment approaches. As no studies which met inclusion criteria were identified for turning there is an urgent indication for primary research studies to explore coordination impairments in turning following stroke in particular, in order to better understand possible mechanisms of falls incidences post-stroke (Hyndman et al. 2002) and to provide rational for treatment approaches to improve the ability to turn.

Whole body coordination during pre planned and reactive turns

In the first study to quantify differences between individuals with hemiparetic stroke compared to healthy individuals in the kinematics of pre-planned and reactive turns while walking, stroke survivors demonstrated similar stepping strategies, order of axial segment reorientation and ability to achieve the required turn amplitude in the same time frame as healthy age and gender matched counterparts regardless of turn direction or times permitted to plan and execute turns. These results indicate that the locomotor programme is still flexible enough, following stroke, to carry out turns even at short notice; as might be required to avoid an oncoming pedestrian or obstacle. Participants with stroke-induced lesions involving the basal ganglia however, initiated pre-planned turns to their non-paretic side significantly later than control participants. This impairment could theoretically promote instability and may

help explain the falls incidences of some community dwelling stroke survivors (Hyndman et al. 2002).

Whole body coordination during 180degree turns in stroke participants with and without falls history

In an attempt to further elucidate potential biomechanical mechanisms which may underlie falls incidences during turning while walking in stroke survivors, a study was undertaken to examine the kinematics of turning in groups of participants with stroke with and without falls history during the TUG test. Community-dwelling, chronic stroke survivors with and without falls history were able to carry out the 180-degree turn during the TUG task in a very similar manner to age-match healthy counterparts. This is a surprising finding since half of the participants with stroke had a falls history and half of those reported falling while turning. Although participants who had a stroke and falls history took significantly longer to turn than age-match controls, no kinematic differences in number of steps taken to turn or in the axial segment coordination were found which could contribute to falls history or falls risk. Therefore, other explanations for falls epidemiology during turning in individuals living at home, who are greater than 6 months post-stroke (Hyndman et al. 2002), need to be explored. It is likely that deficits in cognitive processes such as attention (Hyndman 2003) or central integration (Plummer-D'Amato et al. 2008) and/or sensory deficits(Connell et al. 2008) are contributory factors.

Comparison of findings to current literature

Results of both these primary research studies examining the kinematics of turning under different time allowances, turn magnitudes and sub-groups of stroke patients indicate

that participants who were greater than 6 months post-stroke were able to reorient segments in the same sequence as healthy individuals. The long-term community dwelling stroke survivors who took part in these studies reoriented the head first, followed by the thorax and pelvis together and finally the CoM. Similar to results of previous studies in healthy young adults (Patla et al. 1999; Hollands et al. 2001), stroke survivors were seen to reorient the head towards the new direction of travel sooner when the turn was cued at the beginning of the walk as opposed to only one stride ahead of when a turn was required. When performing turns of a larger magnitude (i.e. 180 degrees) studies of young healthy adults (McCluskey and Cullen 2007; Anastasopoulos et al. 2009) indicate these turns are started by initiating reorientation of axial segments to the new direction of travel in a more en-bloc style. This is a strategy which was adopted by all participants of the second study including those who have had a stroke with and without history of falling. Stroke survivors also rotated the head beyond the trunk in the direction of the turn to a similar extent as control participants and as previously seen in a study of young adults performing 180-degree turns (Sreenivasa et al. 2008). The preserved capacity of participants with stroke to react and organize the modifications of locomotor strategies to perform the turn with the same success as healthy participants is remarkable, especially given that a recent study (Lamontagne and Fung 2009) has suggested that a major deficit in locomotion following stroke is the inability to sequentially reorient axial segments to the new direction of travel. Several important factors may account for the discrepancy in findings between Lamontagne and colleagues, (2009) and the studies presented here.

Firstly, the magnitudes of turns in these studies were different. While evidence from a previous study(Hollands et al. 2001) indicated that magnitude of turn did not appear to alter axial segment coordination in healthy young adults, more recent studies (McCluskey and

Cullen 2007; Anastasopoulos et al. 2009) indicate that standing turns greater than 40 or 50 degrees require more contribution from body rotation and that eye, head and trunk rotations were more enbloc in trials when turns were beyond the visual field (e.g. 90 degrees or greater) and were pre-planned. These findings raise the possibility that adaptations to the basic locomotor pattern required to carry out a 45 degree turn (Study 1) while walking are relatively small and within the abilities of long-term stroke survivors with well established compensatory locomotor patterns to achieve. Whereas the 90 degree turn utilised by Lamontagne et al, (2009) may require larger alterations to the locomotor pattern which uncovered coordination impairments. However, participants of Study 2 were also seen to reorient axial segments in a similar manner to healthy counterparts when carrying out a 180 degree turn. It is unlikely therefore, that magnitude of turn explains the differences in findings between this body of work and that of Lamontagne et al, (2009).

Secondly, there were differences in the method of axial segment reorientation onset latency detection used in the studies of this thesis and that of Lamontagne et al, (2009). In this thesis, the onset of segment yaw reorientation during a turn trial was measured as the point in time of an acceleration reversal (detected as a zero crossing in the third-derivative) which immediately preceded the sustained deviation (at least 25 frames equalling 200ms) of the turn trial data outside of the 3SD boundary of the average straight walking parameter. The advantage of using the zero-crossing in the third-derivative immediately preceding the sustained deviation of the segment yaw profile outside of the SD boundaries is that this point is not influenced by the degree of variability in the segment trajectories during straight walking or the speed of segmental rotation when turning. Detecting the onset latency as the time point when the segment trajectory deviates outside of the 2SD bound, as previously done in several studies(Solomon et al. 2006; Lamontagne and Fung 2009) means that if the

variability of one segment's trajectories is less than another segment or that one segment rotates out of the straight SD bounds with greater speed than another segment, the onset latencies of both segments may be detected at the same point in time leading to an interpretation of en-bloc reorientation. Further analyses were undertaken (and reported in Chapter 3 Methods) in attempt to determine the extent that our method of determining onset latencies may have affected the results compared to previously published detection methods (e.g. the point in time when the segment angular trajectory deviates outside the 2 SD boundary (Solomon et al. 2006; Lamontagne and Fung 2009). This analysis revealed no statistical differences between the outcomes of the two detection methods. Given that the two methods provide the same results, it is unlikely that differences in results of the studies in this thesis and that of Lamontagne et al, (2009) may be due to differences in onset latency detection methods. However, it may still be the case that the onset latency detection methods may provide different results when applied to patient populations with larger variability of axial segment control as may be the case in acute or sub-acute patients who do not yet have well established compensatory locomotor patterns.

A final difference between the studies lies in the chronicity of stroke participants. Participants of the studies in this thesis were greater than two years post-stroke in contrast to participants of Lamontagne et al.'s (2009) study who were less than one year post-stroke. A recent study by Verheyden et al, (2007) indicated that the coordination of head and trunk may be modified early after stroke but recover over time towards the level of healthy subjects. This finding combined with the discrepancy in results between the current study and that of Lamontange et al, (2009) indicates that recovery of axial segment turning synergies may occur up to two years post-stroke. It therefore seems most likely that differences in stages of recovery of axial segment control and how this affects onset latency detection methods may

account for the differences in results between this body of work and that of Lamontange et al, (2009).

Synthesis of Results

Coordination of stepping strategies during turning in participants with stroke

The research studies in this body of work are the only two studies to date that have examined stepping strategies during turning in stroke survivors. Both of these studies found few differences between stroke survivors and healthy counterparts. Although participants with stroke used wider step widths and shorter step lengths at each step preceding a 45-degree turn, they employed the same overall stepping strategy as healthy counterparts.

In the study examining kinematics of 180 degree turns, all groups completed the turn using no more than two steps. Turning with only two steps indicates a pivot strategy was used to carry out the turn (Thigpen et al. 2000). It has been previously suggested (Thigpen et al. 2000) that individuals who accomplish a turn using a multiple step strategy as opposed to a pivot strategy may do so to compensate for a lack of ability to carry out the more ballistic strategy of pivot turn. Although the group of participants with stroke who participated in this study exhibited residual paresis in the lower limb (< 34 on Fugl-Meyer lower extremity scale) and half had a falls history, they all still employed a pivot turning strategy. These results therefore, do not support the hypothesis of Thigpen and colleagues (2000) that turning difficulty may be caused by impaired ability to produce a pivot-turn movement pattern.

The participants of both studies were seen to have well recovered spatial symmetry in their straight gait patterns. If participants were spatially asymmetric this could facilitate turns in one direction when step lengths and widths need to be asymmetric to achieve a turn and hinder in the other direction when they need to alter the step of the limb which is habitually

shorter or wider. However, in the study of 45 degree turns even the stroke participant with the greatest stepping asymmetry showed only small differences between paretic and non-paretic step widths (4mm) during the transition steps. Therefore, it would seem that persistent impairments in symmetry of straight stepping parameters due to hemiparesis may not impair ability to generate appropriate stepping patterns when turning in either direction.

Time to turn

One study (Den Otter et al. 2005) of stroke survivors performing obstacle avoidance tasks has highlighted that the amount of time available for stroke survivors to alter the gait pattern may be crucial for successful performance. Den Otter and colleagues (2005) demonstrated that decreasing the time available to modify the gait pattern to step over an obstacle resulted in significantly higher failure rates than when more time was permitted. This suggests that stroke survivors may need more time to implement changes to locomotor patterns in response to environmental demands. In order to test this hypothesis, participants of Study 1 were asked to perform both pre-planned and reactive turns. Reactive turns were cued only two steps (one stride) before participants reached the turning point in the walkway. Previous studies have demonstrated this to be the minimum time required for healthy young adults to carry out a turn (Patla et al. 1999; Paquette et al. 2008). Similar to results of previous studies in healthy young adults (Patla et al. 1999; Hollands et al. 2001), stroke survivors were seen to reorient the head towards the new direction of travel sooner when the turn was cued at the beginning of the walk as opposed to only one stride ahead of when a turn was required. Stepping strategies used to turn were not different in pre-planned or reactive turn conditions.

The fact that stroke survivors were able to reorient axial segments in similar times to control participants even when the cue to turn was delivered at the last possible moment,

indicates that physiological changes underlying paresis such as an impoverished ability to activate musculature or decreased force production ability of musculature are unlikely to underlie any impairment. Furthermore, these results indicate the locomotor programme is still flexible enough, following stroke, to carry out turns even at short notice; as might be required to avoid an oncoming pedestrian or obstacle.

Magnitude of turn

Studies of young healthy adults have shown that for turns of 60º or less axial segments are proactively rotated to the new direction of travel in a sequential top down pattern with the eyes and head leading, followed by the trunk and pelvis and finally feet (Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Trunk rotations in the frontal plane (roll) serve to preserve stability and aid movement of the centre of mass (CoM) towards the new travel path (Patla et al. 1999; Hollands et al. 2001; Imai et al. 2001). Turns greater than 50º require more contribution from body rotation and eye, head and trunk rotations are more synchronous when turns are beyond the visual field (e.g. 90º or greater) and are pre-planned (McCluskey and Cullen 2007; Anastasopoulos et al. 2009). The two primary research studies presented in this body of work involve 45 (Study 1) and 180 º (Study 2) turns. In both studies participants with stroke were seen to reorient the head first, followed by the thorax and pelvis together and finally the CoM. Similar to results of previous studies in healthy young adults (Patla et al. 1999; Hollands et al. 2001), stroke survivors were seen to adjust anticipatory onset of head reorientation according to variations in the time allowed to plan and carry out the turn. When performing turns of a larger magnitude (i.e. 180 degrees) both healthy participants and those with stroke, started turning by initiating reorientation of axial segments to the new direction of travel in a more en-bloc style, as has been seen in healthy individuals previously

(Anastasopoulos et al. 2009). Stroke survivors also rotated the head beyond the trunk in the direction of the turn to a similar extent as control participants and as previously seen in a study of young adults performing 180-degree turns (Sreenivasa et al. 2008).

Falls history

Study 2 is the first study to examine the kinematics of turning in groups of participants with stroke with and without falls history during the TUG task. Community-dwelling, chronic stroke survivors with and without falls history were able to carry out the 180-degree turn during the TUG task in a very similar manner to age-match healthy counterparts. This is a surprising finding since 50% of community-dwelling stroke survivors fall and a large proportion of those falls occur while turning (Hyndman et al. 2002). Half of our stroke participants had a falls history and half of those reported falling while turning. Although participants who had a stroke and falls history took significantly longer to turn than age-match controls, we found no kinematic differences in steps taken to turn or in the axial segment coordination during turning which could contribute to falls history or falls risk. Therefore, impairments in the generation of appropriate movement patterns while turning are not the main cause of falls and future studies should examine the interplay of impaired movement production with the many other factors (e.g. deficits in cognitive processes such as attention (Hyndman 2003) or central integration (Plummer-D'Amato et al. 2008) and/or sensory deficits (Connell et al. 2008)) which are associated with falls in long-term, community-dwelling stroke survivors.

Neural basis for control of turning coordination

The subgroup of participants from study 1 whose lesions involve the BG were significantly slower to initiate the sequence of axial segment reorientation during pre-planned turns to the non-paretic side than age-match counterparts. Therefore it would seem that the trend observed in the main analysis for reorientation onset differences between stroke and control participants in the early cue condition are driven by differences in the BG sub-group. The BG has been implicated in the control of axial segments during turning (Vaugoyeau et al. 2006; Crenna et al. 2007) and in providing internal cues for the initiation of movement sub-components in well practiced, automatic movement sequences through discharge of activity in the globus pallidus (Georgiou et al. 1993). Recent evidence has indicated that the preferred direction of turning in asymmetric Parkinson's disease patients is ipsilateral to the side of less dopamine activity (Mohr et al. 2003). It is reasonable to assume that a stroke-induced BG lesion would result in altered dopamine activity on the same side of the brain as the lesion (i.e. contralateral to the side of paresis) and therefore a delay in initiating turns to the non-paretic side would be consistent with an explanation based on assymetrical activity of dopaminergic pathways. Given that control participants walked at the same speed as their stroke counterparts and that speed was also included as a covariate in analyses, it is unlikely that the trend seen in participants with BG lesion involvement are due other factors such as this subgroup walked at a slower pace or was more severely impaired than the subgroup with no BG involvement.

Limitations

Although this body of work has expanded the understanding of the characteristics of impairments in the kinematics of turning, there are two main factors which limit

generalizeablity of results. Firstly, sample sizes are small. However, sample sizes are larger, almost double, many other kinematic studies (Patla et al. 1999; Hollands et al. 2001; Vallis and Patla 2004; Lamontagne and Fung 2009). Furthermore, sample sizes were large enough to find statistically significant results when effect sizes were arguably too small to be functionally meaningful. For example, Study 2 revealed between group differences in axial segment onset latencies of 100ms. It is unlikely that such small differences in timing can be improved by conscious efforts/attention to these aspects of movement due to fixed amounts of time needed for neural transmission from premotor cortex (Carlsen et al. 2010). Secondly, inclusion/exclusion criteria may have dictated that characteristics of participants were less than representative of their populations. For example, all participants with stroke performed the study tasks without use of orthopaedic aides such as, ankle-foot orthotics or canes and healthy control participants were largely recruited from community exercise groups. Both of these groups, therefore, may have been fitter than their peers. Furthermore, control participants were included on self-report of clean health and as a result may have had sub-clinical conditions, such as arthritis, which may have affected their ability to walk and turn. However, several papers have supported the choice of less stringently screened control participants as more representative of their population (Craik 1995; Prince 1997). In order to be sure that the results reported are representative of the populations of community dwelling stroke survivors, it would be optimal to repeat the protocol with larger participant numbers and to examine the effects of orthopaedic aides on turning kinematics.

The study is also limited in ecological generalizeability by the fact that turning paradigms were performed in a laboratory environment. Walking and turning in the laboratory is not representative of the task of turning in the home or community where the environment is cluttered and terrain is undulating. The fact that we found no kinematic

differences in turning behaviour according to falls history (in Study 2) in our sample does indicate that the influences such as trip hazards and distractions to attention should be considered in future studies.

Another influencing factor for movement patterns seen during turning is the fact that turns were performed on a delineated walkway. This may have constrained turns to occur in a given area. However, the walkway was 2m in width and more than 6m long in any direction, and is unlikely to have constrained turning patterns in any significant way. Indeed, none of the participants demonstrated or reported difficulty in staying within the pathway or the desire to perform the turns in any way which would require going outside of the walking area.

Some studies (Olney et al. 1994; Barela et al. 2000) have reported that walking speed accounts for a proportion of the variance in inter and intra-limb coordination of stroke survivors' walking and that walking velocity has a significant influence on the coordination of axial segments in healthy adults (van Emmerik and Wagenaar 1996). Therefore in both Study 1 and 2, speed of walking was included as a covariate in the statistical analyses. This served to remove the variability in dependent measures associated with the range of different speeds participants walked at (van Emmerik and Wagenaar 1996) and the variability associated with the range of different severities of motor impairment (reflected by walking speed) between subjects (Perry et al. 1995). Walking speed was not included as a covariate for gait event measures given the mechanistic and confounding link between gait parameters and walking speed (Bayat 2005). In addition, control participants of Study 1 were asked to perform the direction change task at the same walking speed as their stroke participant counterpart. This additional control for the confound of speed was not possible in Study 2 when the speed of performance of the TUG task was in itself a measure. The best way to control for the influence of speed of walking on turning kinematics is not clear. It could be argued that

comparison of participant groups walking at their self-selected paces is more desirable than comparing one participant group walking at their self-selected pace to another group who has been asked to perform the task at a slower pace to match speeds. Time normalizing kinematic data to percent stride time (Imai et al. 2001) is one way to eliminate the confound of speed while allowing participants to perform the task at their natural pace. However, time normalizing in this way presents additional confounds when comparing gait of stroke survivors with different spatio-temporal properties to healthy counterparts. For example, comparing temporal gait events such as onset latencies as a function of stride duration would be problematic since any differences found in these measures would likely be a function of between-group differences in temporo-spatial stepping characteristics. One study (Prévost et al. 2003) has investigated the effects of varying speed on turning kinematics in healthy young adults. The spatial structure of axial segment reorientation trajectories was unaffected when participants walked at speeds slower than their natural pace. The results of work by Prévost and colleagues (2003), therefore, provide evidence for the validity of comparing turning kinematics between stroke participants walking at their self-selected pace to control participants who have been asked to walk at speeds slower than their natural pace. Therefore the effects of speed on turning kinematics reported in studies 1 and 2 are unlikely to alter or invalidate results.

Clinical Implications

If gait coordination is impaired as a result of an underlying pathology, then functionally adaptive walking may also be impaired (Roerdink et al. 2007). Poor motor coordination and ability to adapt the straight gait pattern may therefore be an underlying mechanism causing the high prevalence of falling (Hyndman et al. 2002) during adaptive

locomotor behaviours, such as turning, post-stroke. Therefore, rehabilitation targeted at coordination of axial and lower limb segments would appear to be a mechanistic way of achieving rehabilitation aims for walking post-stroke. Indeed, improving gait coordination and restoring the ability to adapt gait patterns according to environmental and task demands are increasingly being recognized in physical therapy practice as important components of improving locomotor performance (Roerdink et al. 2007).

A systematic review of the literature (Chapter 2) has identified insufficient homogeneity of high quality evidence to determine if task specific locomotor practice interventions are effective in improving aspects of gait coordination or indeed to determine if improvements in motor coordination coincide with improvements in functional walking capacity of chronic stroke patients. Overall, included studies lacked follow-up assessments to examine the transfer of stepping skills obtained in the treadmill environment to the OG domain and inclusion of tasks to develop the ability to adapt to the environment and one's behavioural goals, such as the ability to turn (Plummer et al. 2007). On this basis, there is currently insufficient evidence to make any clinical recommendations regarding the most efficacious intervention to address gait coordination and turning.

The fact that there is a dearth of studies examining efficacy of interventions that specifically target and measure restoration of coordinated gait components (Daly et al. 2006) may be due to the fact that the rational for different treatment approaches is still weak and needs a better understanding of the nature of coordination deficits in functional tasks after stroke (Van Peppen et al. 2004). Therefore, some clinical recommendations may be drawn from the relatively broad base of literature contributing to our understanding of how direction changes are implemented and controlled in healthy young adults. This understanding can be translated into goals to be achieved through rehabilitation efforts. For example, evidence from

studies of healthy adults indicate that anticipatory head movements towards the new direction of travel serve to provide a stable frame of reference for the rest of the body to reorient with respect to (Hollands et al, 2001; Vallis et al, 2004) and that this reference frame is established approximately 1m ahead of the turning point (Sreenivasa et la, 2008) and may be established by the coordination of eye-head and feet (Reed-Jones et al, 2009). This could indicate that rehabilitation efforts should attempt to restore the ability to look ahead at the upcoming path at least 1 m before turning and stabilisation of the head (by making equal and opposite rotations to medio-lateral shifts of the body mass (Imai et al. 2001)) could be key to improving turning ability in stroke survivors.

Studies of healthy individuals have shown that turning involves altering the straight walking pattern to produce asymmetries between the left and right legs in parameters such as step length, step width and ground reaction force (Courtine and Schieppati 2003a; Orendurff et al. 2006). One might suggest that the recovery of spatial symmetry in the straight gait patterns of the stroke survivors could facilitate the ability to carry out the turn using equivalent stepping strategies on both paretic and non-paretic sides. However, even the stroke participant with the greatest stepping asymmetry, in Study 1, showed only small differences between paretic and non-paretic step widths (4mm) during the transition steps. Therefore, it would seem that persistent impairments in symmetry of straight stepping parameters due to hemiparesis may not impair ability to generate appropriate stepping patterns when turning in either direction.

Longer time to turn (Berg 1989; Lipsitz et al. 1991; Thigpen et al. 2000; Dite and Temple 2002) and use of a multiple step strategy as opposed to a pivot strategy may indicate turning difficulty and falls risk. Rehabilitation efforts should therefore aim to improve speed of walking and turning and encourage achievement of turns within two steps in which the

foot-step contralateral to the turn direction is made wider than previous steps to drive the CoM towards the new direction of travel (Hollands et al. 2001). This strategy provides a wide base of support within which the CoM can move without approaching the limits of stability, but requires the ability to lengthen and widen the step of the limb on the outside of the turn and shorten on the limb to the inside of the turn. This points to the idea that rehabilitation should focus on the ability of patients to alter step widths and lengths of *both* paretic and non-paretic limbs in order to be able to safely achieve turns in either direction.

The studies in this body of work are the first to contribute clear evidence of characteristic coordination deficits during turning and walking following stroke. Findings from Study 1 showed a strong trend indicating that participants with stroke (significantly in those whose lesions involve the BG) tended to reorient the head later in pre-planned turns than their age-match counterparts. In contrast no such differences in axial segment onset latencies were seen between stroke patients and healthy counterparts in the reactive/visually-cued turn condition. Importantly, the difference in timing of axial segment reorientation of participants with stroke between turn conditions highlights the potential for visual cues to improve turning ability following stroke. We hypothesize that the normalization of turning synergy seen in the visually cued turn condition is achieved by one of three mechanisms by: (a)externally cueing the required movement and thus overcoming potentially impaired internal cueing of movement sequences (hypothesized to account for similar deficits in turning ability in patients with PD (Vaugoyeau et al. 2006), (b) focusing attention away from the ongoing step and onto the required upcoming change to the locomotor pattern (results of a dual-task study (Regnaux et al. 2005) showed that stroke survivors' performance of a secondary task was diminished in favour of maintaining characteristics of ongoing steps) or, (c) triggering a gaze redirection which may elicit the start of the reorientation sequence (as

hypothesized by Reed-Jones et al, (2009)). Further studies are required to test these hypotheses before the efficacy of visual cues as a potential intervention to improve turning ability for stroke survivors can be assessed.

Studies have suggested that the areas of the brain involved in controlling direction change may include both cortical *and* subcortical structures, with some specific evidence for the involvement of the BG and cerebellum (Crenna et al. 2007; Reisman et al. 2007). Results from Studies 1 and 2 indicate that patients with lesions involving the BG were slower to initiate pre-planned turns to the non-paretic side; possibly due to asymmetric dopamine activity and consequent impaired ability to initiate movement sequences (Georgiou et al. 1993; Mohr et al. 2003). This suggests that rehabilitation should emphasize practicing initiation of gait and turning synergies particularly in patients with middle cerebral artery infarcts as this blood supply serves both the cortex and BG and therefore may leave these patients with particular impairments in the ability to initiate turns.

Only one study to date (Lamontagne and Fung 2009) has examined turning ability during walking in the first year following stroke and this study suggested that a major deficit in locomotion of sub-acute patients is the inability to sequentially reorient axial segments to the new direction of travel. Results from study 1 and 2 indicate that participants who experienced a stroke more than 2 years ago are able to control axial segment reorientation in a way that is very comparable to healthy controls. The discrepancy in results between this body of work and that of Lamontagne et al, (2009) suggest that control of axial segment turning synergies may continue to be recovered/rehabilitated beyond the acute stages of stroke. This corroborates other studies indicating that coordination of head and trunk may be modified early after stroke but recover over time towards the level of healthy subjects (Verheyden et al. 2007) and that many stroke survivors can improve ambulatory function beyond the usual

recovery period if they receive intensive walking practice (Peurala 2005; Plummer et al. 2007; Patterson et al. 2008b). It could be suggested therefore that rehabilitation efforts should continue beyond 6 months post-stroke and emphasize the ability to sequentially rotate axial segments in order to conduct a turn.

Turning movement patterns may have been largely regained longer than 6 months post-stroke, but falls still continue. Results from Study 2 indicate that stepping and axial segment control during turning was similar in participants with stroke and falls history to healthy controls. Therefore, incidences of falls during turning following stroke may not be due to impaired movement patterns alone. On this basis, it can be suggested that clinical rehabilitation efforts, as well as further studies, should address the interplay of impaired movement production with the many other factors which are associated with falls in long-term, community-dwelling stroke survivors. Results (discussed above) indicating that delayed initiation of turning, especially in participants whose lesions involved the BG, may have been due to impaired cueing of movement sequences and/or attention to upcoming required movements, point to the idea that rehabilitation should concentrate particularly on the interaction between movement production and attention.

Future Directions

Findings of the systematic literature review revealed a need for:

- high quality RCTs to determine the effect of: TT compared to OG training on improving locomotor coordination impairments in chronic stroke patients.
    - The precise mechanisms by which regular, self supported, TT or OG training could lead to improvements in lower-extremity motor function in

chronic stroke patients should be documented reporting gait parameters for both limbs.

- Future RCTs should include follow-up assessments to examine the transfer of stepping skills obtained in the treadmill environment to the overground domain and on the ability to adapt the locomotor pattern to achieve turns or step over obstacles.

- sensitivity analyses on the effect of combining measures of gait symmetry calculated in different ways and there is a need for further research to identify optimal methods of calculating outcome measures for use within future RCTs in this area.
- research studies to explore the characteristics of coordination deficits in functional tasks, such as turning, after stroke (van Peppen et al, 2004) in order to better provide rational for different treatment approaches.

The two experimental studies aimed at fulfilling the final recommendation of the systematic review were undertaken in order to better understand stroke-related impairments in coordination during turning. Although this body of work has expanded the understanding of the characteristics of impairments in the kinematics of turning, many additional questions regarding the control of turning in populations of chronic community-dwelling stroke survivors have been raised by the results of this work. Specific questions to be addressed include:

- The discrepancy in results regarding axial segment control between this body of work and that of Lamontagne et al, (2009) indicates the need for a longitudinal study to explore recovery of turning synergies from 6 months to 2 years post-stroke.

- Results of Study 1 indicating initiation of turns was better in the visually cued turn condition than in the pre-planned turn condition indicate a need to explore the concept of using visual cues to improve turning ability following stroke
- Results of Study 2 indicating that participants with stroke and falls history were able to generate movement patterns during turning which were comparable to controls and stroke participants without falls history indicate further studies, should address the interplay of impaired movement production with the many other factors which are associated with falls in long-term, community-dwelling stroke survivors, with particular examination of attentional focus (e.g. through dual task paradigms).
- Results of Study 1 indicating impairment in turn initiation was particular to the sub-group of participants whose lesions involved the BG highlight the importance of considering lesion location when studying, and attempting to rehabilitate, the movement deficits of individuals who have suffered a stroke. Further studies are required to identify lesion-specific impairments in turning and walking ability. This can be achieved by selecting participants with homogeneous lesion locations.
- Due to the uncertainty of the effect of orthopaedic aides on turning kinematics, participants were only included in studies if they were able to walk in the laboratory without assistance from any such devices. Future studies are required to determine how orthopaedic aides influence turning kinematics.
- Results of Study 1 indicating participants, with relatively mild gait asymmetries, were able to generate appropriate stepping strategies in either direction, indicate future studies should examine how stepping strategies for turning of participants with more severe gait asymmetries and slower self-selected walking speed are affected.

Conclusions

A systematic review of the literature has identified insufficient homogeneity of high quality evidence to determine if task specific locomotor practice interventions are effective in improving aspects of gait coordination or indeed to determine if improvements in motor coordination coincide with improvements in functional walking capacity of chronic stroke patients. Overall, included studies lacked follow-up assessments to examine the transfer of stepping skills obtained in the treadmill environment to the OG domain and inclusion of tasks to develop the ability to adapt to the environment and one's behavioural goals, such as the ability to turn(Plummer et al. 2007). The fact that there is a dearth of studies examining efficacy of interventions that specifically target and measure restoration of coordinated gait components (Daly et al. 2006) may be due to the fact that the rational for different treatment approaches is still weak and needs a better understanding of the characteristics coordination deficits in functional tasks, such as turning, after stroke (Van Peppen et al. 2004).

The studies in this body of work are the first to contribute clear evidence of characteristic coordination deficits during turning and walking following stroke, which may underlie falls incidences. Results of both these studies examining the kinematics of turning under different time frames, turn magnitudes and sub-groups of stroke patients indicate that participants who were greater than 6 months post-stroke were able to reorient segments in the same manner as healthy individuals in most conditions. The preserved capacity of participants with stroke to react and organize the modifications of locomotor strategies to perform the turn with the same success as healthy participants is remarkable.

Turning movement patterns may have been largely regained longer than 6 months post-stroke, but falls still continue (Hyndman et al. 2002). Findings from Study 1 showed a strong trend indicating that participants with stroke (in particular those whose lesions involve

the BG) tended to reorient the head later in pre-planned turns than their age-match counterpart. In contrast no such differences in axial segment onset latencies were seen between stroke patients and healthy counterparts in the reactive/visually cued turn condition. Importantly, the difference in timing of axial segment reorientation of participants with stroke between turn conditions highlights the potential for visual cues to improve turning ability following stroke. Furthermore, these findings highlight the importance of considering lesion location in future studies and rehabilitation efforts. It is therefore, suggested that clinical rehabilitation efforts, as well as further studies, should address the interplay of impaired movement production with the many other factors which are associated with falls. Further studies investigating the role of lesion location and attentional focus on the control of body coordination during turning in chronic stroke survivors may provide much needed information in order to design targeted interventions to remediate these deficits.

APPENDICIES

Appendix I Medline& EMBASE search strategy.

The following search strategy was used, using a combination of controlled vocabulary (MeSH) and free text terms, for MEDLINE & EMBASE and was modified to suit other databases (see Appendix II).

2. cerebrovascular disorders/or exp basal ganglia cerebrovascular disease/ or exp brain ischaemia/ or exp carotid artery diseases/ or cerebrovascular accident/ or exp brain infarction/ or exp cerebrovascular trauma/ or exp hypoxia-ischaemia, brain/ or exp intracranial arterial diseases/ or intracranial arteriovenous malformations/ or exp "Intracranial Embolism and Thrombosis"/ or exp intracranial haemorrhages/ or vasospasm, intracranial/ or vertebral artery dissection/
3. (stroke or poststroke or post-stroke or cerebrovasc$ or brain vasc$ or cerebral vasc$ or cva$ or apoplexy$ or SAH).tw
4. ((brain$ or cerebr$ or cerebell$ or intracran$ or intracerebral) adj5 (isch?emi$ or infarct$ or thrombo$ or emboli$ or occlus$)).tw
5. ((brain$ or cerebr$ or cerebell$ or intracerebral or intracranial or subarachnoid) adj5 (haemorrhage$ or hemorrhage$ or haematoma$ or bleed$)).tw
6. hemiplegia/ or exp paresis/
7. (hemipleg$ or hemipar$ or paresis or paretic or "motor recovery" or recovery).tw
8. 1 or 2 or 3 or 4 or 5 or 6
9. (axial/ or trunk/ or pelvis/ or head).tw
10. exp lower extremity/
11. (lower adj3 (limb$ or extremity)).tw
12. (leg or hip or knee or ankle or foot).tw
13. 8 or 9 or 10 or 11
14. 7 and 12
15. (coord$ or "bilateral coordination" or "intralimb coordination" or intralimb).tw
16. (symm$ or asymm$).tw
17. 14 or 15
18. exp walking/ or gait/ or locomot$
19. (walking or gait or locomot$).tw
20. 17 or 18
21. 13 and 16 and 19

Appendix II CINAHL & AMED search strategy

1. (MM "cerebrovascular disorders+" or (MM "cerebral ischemia+") or basal ganglia cerebrovascular disease or carotid artery diseases or **stroke or stroke patients** or **cerebral embolism** or **brain injuries** or intracranial arterial diseases or **intracranial arteriosclerosis** or **arteriovenous malformations or cerebral embolism and thrombosis** or intracranial haemorrhages or **cerebral vasospasm** or vertebral artery dissection) +
2. TI stroke or poststroke or post-stroke or cerebrovasc* or brain vasc* or cerebral vasc* or cva* or apoplexy* or SAH
3. AB stroke or poststroke or post-stroke or cerebrovasc* or brain vasc* or cerebral vasc* or cva* or apoplexy* or SAH
4. brain* or cerebr* or cerebell* or intracran* or intracerebral N5 isch?emi* or infarct* or thrombo* or emboli* or occlus*
5. brain* or cerebr* or cerebell* or intracerebral or intracranial or subarachnoid N5 haemorrhage* or hemorrhage* or haematoma* or bleed*
6. MM hemiplegia or paresis
7. hemipleg* or hemipar* or paresis or paretic or "motor recovery" or recovery
8. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 = *combines all stroke terms*
9. axial or trunk or pelvis or head
10. MM lower extremity +
11. lower N3 limb* or extremity
12. leg or hip or knee or ankle or foot
13. 9 or 10 or 11 or 12 = *combines all lower limb terms*
14. 8 and 12 = *all stroke AND lower limb terms*
15. coord* or "bilateral coordination" or "intralimb coordination" or intralimb or **coupl***
16. symm* or asymm*
17. 15 or 16 = *combines all coordination terms*
18. MM walking + or MM Locomotion +
19. **MM "Gait analysis" or MM "Gait Training" or MM "Ambulation: Walking" or MM "Functional Training"**
20. walking or gait or locomot*
21. 18 or 19 or 20 = *combines all walking terms*
22. 14 and 17 and 21 = *combines all stroke AND lower limb AND coordination AND walking terms*

Appendix III: JBI Critical Appraisal Tool: Comparable Cohort/Case Control studies

	Criteria	Yes	No	Unclear
1)	Is sample representative of patients in the population as a whole?	☐	☐	☐
2)	Are the patients at a similar point in the course of their condition/illness?	☐	☐	☐
3)	Has bias been minimised in relation to selection of cases and of controls?	☐	☐	☐
4)	Are confounding factors identified and strategies to deal with them stated?	☐	☐	☐
5)	Are outcomes assessed using objective criteria?	☐	☐	☐
6)	Was follow up carried out over a sufficient time period?	☐	☐	☐
7)	Were the outcomes of people who withdrew described and included in the analysis?	☐	☐	☐
8)	Were outcomes measured in a reliable way?	☐	☐	☐
9)	Was appropriate statistical analysis used?	☐	☐	☐

Include Undefined

Reason

Update Cancel

Reviewer: Date:
Author:
Year:
Record Number:

Appendix IV: Characteristics of included studies

Study	Chen et al, 2005
Aims	assessed the potential of body weight support, treadmill speed, support stiffness, and handrail hold to improve the identified (Chen et al, 2005a) gait coordination deviations associated with hemiparesis
Methods	multi-factorial experimental design
Participants	n=6 Inclusion criteria for this study were (1) a single stroke at least 6 months prior to study, (2) ability to walk independently overground with use of an ankle foot orthosis (AFO) or assistive device, and (3) ability to advance the paretic limb independently while walking on a treadmill.
Interventions	Treadmill walking, BWS 20, 35 or 50%, stiffness 11.or 35.1N/ms speed 70, 100 or 130% and handrail hold. 10 conditions with different combinations of the above paramters
Authors' Conclusions	The adjustment of each training parameter was found to improve a specific set of the gait deviations. With increased body weight support or the addition of handrail hold, percentage single limb support time on the paretic limb increased and temporal symmetry improved. With increased treadmill speed, leg kinetic energy at toe-off in the paretic limb increased but remained low relative to values in the non-paretic limb. With increased support stiffness, the exaggerated energy cost associated with raising the trunk during pre-swing and swing of the paretic limb was improved. We conclude that the proper selection of training parameters can improve the gait pattern practiced by individuals with hemiparesis during treadmill training and may improve treatment outcome
Notes	20s of walking in each condition only. no follow up assessment of maintenance of effect or transferability to OG walking. control comparison is free treadmill walking.

Risk of bias

Item	Author's judgement	description
aims	yes	clear coordination aim
theoretical basis	yes	based on previous paper identifying gait deficits
baseline characteristics described	yes	in previous paper
randomized order of trials	unclear	not stated
control condition	yes	free treadmill walking
blinding of assesor	no	
reliable measurements	yes	3D motion analysis
valid measurements	yes	7 linked segment biomechanical model
appropriate statistics	unclear	Because of the small sample size in this pilot study, full statistical analyses of the data were inappropriate.
findings well described	unclear	means in table 3 for significant effects not provided

Study	Ford et al, 2007
Aims	The objective was to investigate the effects of auditory rhythms and arm movement on inter-segmental coordination during walking in persons who have suffered a stroke
Methods	Simple experimental design
Participants	N= 11 participants who had suffered a stroke more than 1 year from data collection (six left side involved, five right side involved) were recruited as a sample of convenience. Individuals were included when they (1) were able to walk independently at 0.63 m/s or higher, (2) had no severe perceptual deficits, (3) had no complicating medical history such as cardiac or pulmonary disorders, and (4) had sufficient motivation to participate
Interventions	In experimental conditions 1 and 2, subjects walked on the treadmill at a constant speed (0.63 m/s) and were instructed to step to the beat condition 1) and move their arms and legs to the beat (condition 2) of a metronome that was systematically increased from 1 to 2.2 Hz, then back down to 1 Hz in increments of 0.2 Hz
Authors' Conclusions	Moving the arms and legs to the beat resulted in increased arm swing along with 1:1 frequency coordination between the arm and leg, and a more out-of-phase relation between transverse pelvic and thoracic rotation was observed with larger pelvic and thoracic rotations. Verbal instructions to move the arms to the beat of a metronome leads to increased arm swing, increased stride length, but further study is needed to examine the dynamics of the changes in arm movement, to enhance understanding of how upper extremity movement dysfunction affects inter-segmental coordination during walking.
Notes	only compare condition stepping to the beat and moving arms and legs to the beat . Therefore, control condition is also a manipulation. only 30s of each condition.

Risk of bias

Item	Author's judgement	description
aims	yes	Clear coordination aim
theoretical basis	yes	coupling between an external rhythm and rhythmic movement can be an effective 'tool' for improving motor performance when neural circuitry controlling rhythmic movements is damaged
baseline characteristics described	no	No time since stroke, no indicators apart from TM speed of impairment levels
randomized order of trials	no	The investigators aimed to examine changes in coordination relative to increasing and decreasing metronome frequency. Therefore, systematic increases and decreases in metronome frequency were chosen over random assignment of frequency levels
control condition	yes	But step to the beat is the only control – so still auditory cueing in place
blinding of assesor	no	
reliable measurements	yes	3D motion analysis
valid measurements	yes	
appropriate statistics	Yes	Anova
findings well described	unclear	Many measures (e.g. mean relative phase not described analysis)

Study	Harris-Love et al, 2007
Aims	The purpose of the study was to determine whether TM walking alters the temporal and force parameters of hemiparetic gait. In light of motor learning principles, it was hypothesized that the TM may induce a more symmetrical gait pattern because of the imposition of new task constraints.
Methods	Simple experimental design. Fixed order of performing OG walking followed by TM walking
Participants	N=18, Twelve male and six female subjects (11 with left hemiparesis, seven with right hemiparesis), with persistent gait deviations after hemispheric ischemic stroke, were referred from clinics. All subjects had been discharged from conventional rehabilitation programs. Each subject underwent a complete medical and neurologic evaluation before the start of the study, including a customized cardiac TM exercise stress. Exclusion criteria included unstable angina pectoralis, congestive heart failure, peripheral arterial occlusive disease (> Fontaine II), dementia (MMSE, <22), severe aphasia defined as the inability to follow two-step commands, and chronic pain or orthopaedic conditions that could alter gait patterning.
Interventions	For the OG trials, subjects were instructed to walk at their most comfortable, preferred speed down the gait mat. Five 00 walking trials were collected for each subject Subjects were then asked to walk on the TM with the velocity set to match their mean OG walking velocity. Use of the handrails was allowed for postural stability. Three TM walking trials were performed
Authors' Conclusions	TM induces an immediate alteration toward a more consistent and symmetric gait pattern. Further investigation is needed to determine whether TM training leads to motor relearning and neuroplasticity in chronic hemiparetic subjects
Notes	5 trials of each type of walking - no follow up for maintenance of effect

Risk of bias

Item	Author's judgement	description
aims	yes	Coordination aim referred to via temporal and symmetry of gait
theoretical basis	yes	Motor learning principles of TM training
baseline characteristics described	no	No only mean time since stroke or and SSWS as indicator of impairment.
randomized order of trials	No	
control condition	yes	OG
blinding of assesor	No	
reliable measurements	yes	Force sensitive walkway measuring gait parameters
valid measurements	Yes	
appropriate statistics	Yes	Two-tailed, paired Student t-tests were used to test for differences between the two gait conditions with P = 0.05.
findings well described	Yes	

Study	Lindquist et al, 2007
Aims	evaluate the effects of the combined use of FES and treadmill training with BWS on walking functions and voluntary limb control in people with chronic hemiparesis.
Methods	A1-B-A2 single-case study design
Participants	after chronic stroke (2 women and 6 men, age [X ±SD] 56.6±10.26 years, stroke interval 17.3±10.9 months) took part in the study. Two subjects had right-side hemiparesis, and 6 subjects had left-side hemiparesis, which was caused by right or left supratentorial ischemic stroke (n=6) or intracerebral hemorrhage (n=2).
Interventions	Phases A1 and A2 included 3 weeks of gait training on a treadmill with BWS, and phase B included 3 weeks of treadmill training plus FES applied to the peroneal nerve
Authors' Conclusions	The combined use of FES and treadmill training with BWS led to an improvement in motor recovery and seemed to improve the gait pattern of subjects with hemiparesis, indicating the utility of this combination method during gait rehabilitation. In addition, this single-case series showed that this alternative method of gait training TT with BWS and FES may decrease the number of people required to carry out the training.
Notes	because BWS TT +FES took place after 3 weeks of BWS TT - unable to determine if effects are because of cumulative effects of gait training. only valid comparison is difference between scores at end of A1 and end of B1

Risk of bias

Item	Author's judgement	description
aims	yes	Coordination aim confirmed by outcome measures
theoretical basis	yes	Motor learning principles justify combination of BWS +FES
baseline characteristics described	Yes	Table 1
randomized order of trials	No	
control condition	No	Pre-post comparison
blinding of assesor	No	
reliable measurements	yes	3D motion analysis
valid measurements	Unclear	Bespoke system not commercially validated
appropriate statistics	Yes	ANOVA
findings well described	yes	

Study	Plummer et al, 2007
Aims	secondary aim of this study was to obtain pilot data on the effects of locomotor impairment severity and training duration (12, 24, 36 sessions) on recovery of walking speed, endurance, spatiotemporal characteristics of gait, and paretic leg propulsion in people with moderate or severe gait speed impairment after stroke
Methods	Pilot/feasibility study
Participants	N=7 >3months < 7months since stroke included, participants also had to have residual paresis in the lower extremity, be able to sit unsupported for 30 seconds, follow a 3-step command, and be able to walk at least 10 feet with maximum 1 person assist. Only individuals whose self-selected usual gait speed was less than 0.8 m/s were included; individuals walking slower than 0.4 m/s were considered to have severe gait speed impairment, whereas those walking between 0.4 and 0.8 m/s were considered to have moderate gait speed impairment excluded if they were dependent in self-care or living in a nursing home prior to their stroke. Additional exclusion criteria extensive but exclude all other comorbidities.
Interventions	walking on the treadmill with BWS for 20 to 30 minutes. TT was followed immediately by 10 to 15 minutes of OG training and home exercise instruction. All patients participated in locomotor training 3 days per week for a total of 36 sessions. Patients were required to complete the 36 sessions in no more than 16 weeks and to miss not more than 3 consecutive sessions
Authors' Conclusions	combining the BWST walking with OG walking practice can enhance adaptability in the OG environment. This finding also underscores the importance of having a conceptual framework to provide rationales for particular training strategies.
Notes	Small sample size. ABA comparison

Risk of bias

Item	Author's judgement	description
aims	yes	Aims clearly described
theoretical basis	yes	Motor learning & task specificity
baseline characteristics described	yes	Table 1
randomized order of trials	no	
control condition	No	AbA comparison
blinding of assesor	no	
reliable measurements	Yes	Force sensitive walkway for gait analysis
valid measurements	yes	
appropriate statistics	Unclear	Descriptive statistics only
findings well described	yes	

Study	Reisman et al, 2007
Aims	secondary purpose of this study is to investigate whether after-effects following split-belt treadmill walking lead to improvements in gait symmetry in subjects following stroke
Methods	Multifactorial experimental design
Participants	N=13 single stroke more than 6 months prior to the study (four females and nine males)excluded if they had ther neurological conditions, orthopaedic conditions affecting the legs or back, uncontrolled hypertension, pacemaker or automatic defibrillator, active cancer, radiological and/or physical examination evidence of damage to the cerebellum or were unable to complete the task. Subjects who customarily wear an ankle-foot orthosis (AFO) were allowed to wear it during testing
Interventions	Subjects were asked to walk on a custom-built treadmill (Woodway USA, Waukesha, WI) comprised of two separate belts, each with its own motor, that permitted the speed of each belt (i.e. each leg) to be controlled independently. During different testing periods, subjects walked on the treadmill with the two belts either moving at the same speed (tiedconfiguration) or different speeds (split-belt configuration). During the tied configuration, treadmill belt speeds were either slow (0.5 m/s) or fast(1.0 m/s). In the split-belt configuration, one treadmill belt was set at the slow speed while the other was set at the fast speed.
Authors' Conclusions	Since after-effects are assessed Post-adaptation (i.e. belts tied at the same speed), alterations in the walking pattern would be due to changesin motor commands; they would not simply be a mechanical phenomenon, as might be seen during splitbelt portions of the paradigm. In this study, we have demonstrated that cerebral and subcortical strokes causing a range of sensory and motor deficits did not impair a persons ability to make immediate reactions or slower adaptations during split-belt treadmill locomotion. Importantly, we found that stroke subjects could temporarily store new interlimb relationships, demonstrating that the compromised nervous system is still capable of producing a more normal pattern
Notes	

Risk of bias

Item	Author's judgement	description
aims	yes	Coordination verified from outcome measures
theoretical basis	yes	Motor learning principles
baseline characteristics described	yes	Table 1
randomized order of trials	No	
control condition	No	ABA comparison
blinding of assessor	No	
reliable measurements	Yes	3D motion analysis
valid measurements	Yes	
appropriate statistics	yes	Anova
findings well described	Yes	

Study	Roerdink et al, 2007
Aims	The purpose of this study was to evaluate the efficacy of acoustically paced treadmill walking as a method for improving gait coordination in people after stroke
Methods	Mutlifactorial experimental design
Participants	N=10 able to walk independently (ie, Functional Ambulation Category 526). All participants reported having no hearing deficits.
Interventions	Walk as naturally as possible for 90 seconds at each of the 3 experimental belt speeds (ie, slow, comfortable, and fast). The order of the belt speeds was randomized across the participants. Subsequently, the participants walked on the treadmill with acoustic pacing for about 3 minutes. The belt speed was set at the CWS determined for each participant while the frequency of acoustic pacing was increased from 90% via 100% to 110% of the preferred stride frequency (ie, slow, preferred, and fast pacing) observed during the comfortable belt speed trial. Participants walked exactly 60 seconds at their preferred stride frequency
Authors' Conclusions	The results suggest that acoustically paced treadmill walking provides an effective means for immediately modifying stride frequency and improving gait coordination in people after stroke and, therefore, may be usefully applied in physical therapist practice.In showing that paced treadmill walking is an efficient method for modulating gait in people after stroke, we provided further empiricalsupport for the use of external auditory rhythms in stroke rehabilitation
Notes	Sample of people after stroke was relatively small and heterogeneous, and generalization of the efficacy of paced treadmill walking to the general population of people after stroke is unwarranted

Risk of bias

Item	Author's judgement	description
aims	Yes	Explicit coordination aim
theoretical basis	Yes	Motor learning
baseline characteristics described	Yes	Table 1
randomized order of trials	Yes	
control condition	yes	Pacing versus no pacing
blinding of assessor	No	
reliable measurements	yes	3D motion analysis
valid measurements	Yes	
appropriate statistics	Yes	
findings well described	yes	

Study	Waajford et al, 1990
Aims	The purpose of this study was to investigate the effects of treadmill training on temporal-distance gait variables
Methods	ABA case study
Participants	Unilateral hemiparesis after a CVA, with onset at least 6 months prior to participation in the study able to walk independently with no assistive devices and to be capable of using a treadmill without relying on the railing. Patients with unstable medical conditions or other major pathological conditions were excluded from the study, as were patients with major perceptual disorders, marked cognitive disturbances, apraxia, receptive aphasia, or decreased attention span. The subject had to be sufficiently informed and motivated to complete the study
Interventions	During the baseline (A-I) and treatment-withdrawal (A-II) phases, the subject came in solely for collection of footprint data. During the treatment phase (B), treadmill training and collection of footprint data were both included in the visit. training three times weekly for 3 weeks on a motor-driven Burdick treadmill, which was kept level - 10 minutes on treadmill
Authors' Conclusions	conclude that a small, but statistically significant, treatment effect was demonstrated for base of support and right step length. Much of the treatment effect appeared to result from improved step symmetry. Our study findings support the efficacy of treadmill training for improving some gait characteristics in this particular patient
Notes	intervention duration minimal, single subject, measures from ink on feet leaving footprints on paper

Risk of bias

Item	Author's judgement	description
aims	Yes	Coordination aim confirmed by outcome measures
theoretical basis	yes	Motor learning
baseline characteristics described	Yes	
randomized order of trials	No	
control condition	No	ABA comparison
blinding of assessor	No	
reliable measurements	No	Ink blots on walking mat
valid measurements	Unclear	
appropriate statistics	Yes	
findings well described	yes	

Study	Hornby et al, 2008
Aims	The purpose of the present study was to determine the extent of walking-related improvements obtained after therapist- versus robotic-assisted LT in individuals with severe to moderate gait dysfunction poststroke
Methods	RCT
Participants	N=24 per group Subjects with hemiparesis of 6 months duration after unilateral, supratentorial, ischemic, or hemorrhage stroke were recruited. Lesion location was confirmed by radiographic findings, with no evidence of bilateral or brain stem lesions. All subjects were required to walk 10 m overground without physical assistance at speeds 0.8 m/s at their self-selected velocity (SSV), using assistive devices and bracing below the knee as needed. Exclusion criteria included: significant cardiorespiratory/metabolic disease, or other neurological or orthopedic injury that may limit exercise participation or impair locomotion; size limitations for the harness/counterweight system or robotic orthosis,21 no botulinum toxin therapy in the lower limbs 6 months prior to enrollment; scores 23 on the Mini Mental Status examination (MMSE)28; and, subjects could not receive concurrent physical therapy. All subjects required medical clearance to participate.
Interventions	LT in both treatment groups consisted of 12 sessions (30 minutes/ session) with therapist- or robotic-assistance.
Authors' Conclusions	In the present study, greater improvements in overground gait speed and impaired single limb stance were observed in ambulatory stroke survivors who received therapist- versus robotic-assisted LT. Although larger changes were observed in subjects with less severe gait deficits, the lack of interaction between main factors of treatment and locomotor impairment indicates that therapist-assisted LT was superior for all chronic ambulatory subjects. Changes in step length asymmetry in subjects with severe versus moderate gait impairments.
Notes	

Risk of bias

Item	Author's judgement	description
Allocation concealment	yes	Subjects were stratified according to initial gait speed. Randomization was performed upon enrollment using sealed envelopes concealed from view
Blinding of outcome assessors	no	Blinding of researchers who performed the assessments was not feasible secondary to personnel constraints
baseline characteristics equal	yes	
Intention to treat analysis	no	Only participants completing the study were analysed

Study	Westlake et al, 2009
Aims	Objectives of this pilot study were to: 1) compare the efficacy of Lokomat versus manual assisted-BWSTT in persons with chronic locomotor deficits post-stroke
Methods	Pilot RCT
Participants	N= 8 per group Single cortical or subcortical stroke (confirmed by CT or MRI) greater than 6 months prior to the study, who were categorized as at least unlimited household ambulators (e.g. > 0.3 m/s) [4] participated. Exclusion criteria included: 1) unstable cardiovascular, orthopedic, or neurological conditions, 2) uncontrolled diabetes that would preclude exercise of moderate intensity, or 3) significant cognitive impairment affecting the ability to follow directions
Interventions	Both groups received 12 sessions (3×/wk over 4 weeks) involving 30 min of stepping per session. At least one 2– 3 minute break was provided after 15 min. Total set-up and treatment time never exceeded 1 hr. Training speeds were maintained below 0.69 m/s (2.5 km/h) in the slow groups and above 0.83 m/s (3 km/h) in the fast groups Participants assigned to the Lokomat group trained in a robotic orthosis Participants in the manual-BWSTT group were treated by 1–2 skilled physical therapists/trainers who provided manual guidance of the more affected limb, trunk stabilization/alignment, and verbal and visual cues to normalize stepping kinematics
Authors' Conclusions	Although statistically significant differences were not apparent between Lokomat and manual groups in this small, pilot trial, our data revealed significantly greater training-related improvements within the Lokomat, but not the manual group. Differential treatment effects produced include: 1) Lokomat group improvements in: self-selected overground walking speed, gait symmetry (SLRabs), fast overground walking speed, lower extremity motor impairment (Fugl-Meyer), function (short physical performance battery), and balance (Berg Balance Scale), and 2) manual group improvements solely in balance outcomes (Berg Balance Scale).
Notes	Unclear concealment and blinding

Risk of bias

Item	Author's judgement	description
Allocation concealment	unclear	Computer generated random order. randomization list was overseen by one of the investigators who had no contact with participants until group assignment was revealed.
Blinding of outcome assessors	unclear	Further, group assignment was not revealed to study personnel until the participant was consented and baseline testing was complete
baseline characteristics equal	Yes	
Intention to treat analysis	Yes	No drop outs

Study	Yang et al, 2007
Aims	The purpose of the present study was to examine the effectiveness of a dualtask– based exercise program on walking ability in subjects with chronic stroke.
Methods	RCT
Participants	N=13 in dual task n= 12 in control inclusion criteria were (1) hemiparetic from a single stroke occurring at least a year earlier, (2) limited (gait velocity between 58 and 80cm/s) or full community ambulatory ability (minimum gait velocity of 80cm/s) by Perry et al's classification system,6 (3) not presently receiving any rehabilitation services, (4) able to walk 10m independently without an assistive device, (5) functional use of the involved upper extremity, (6) stable medical condition to allow participation in the testing protocol and intervention and (7) an ability to understand instructions and follow commands. The exclusion criteria were (1) patient with any comorbidity or disability other than stroke that would preclude gait training, (2) any uncontrolled health condition for which exercise is contraindicated, and (3) any neurologic or orthopedic diseases that might interfere with the study.
Interventions	Subjects in the experimental group participated in 30 minutes of a ball exercise program 3 times a week for 4 weeks. The training program was based on a dual-task concept; subjects walked while manipulating either 1 or 2 balls. The balls used in this study were therapy balls with 45-, 55-, 85-, and 95-cm diameters and a basketball. The training program included (1) walking while holding 1 or 2 balls on both hands, (2) walking to match the rhythm of bouncing 1 ball with 1 hand or both hands, (3) walking while holding 1 ball on 1 hand and concurrently bouncing another ball with the other hand, (4) walking in time while kicking a basketball (the basketball was put into a net, and the net was held by the subject) (fig 2), (5) walking while holding 1 ball and concurrently kicking another basketball within a net, (6) walking while bouncing 1 ball and concurrently kicking another basketball within a net, and (7) walking while reciprocally bouncing 1 ball with both hands. Control condition received no intervention.
Authors' Conclusions	Our results showed that a 4-week ball exercise program improved walking ability under single- and dual-task conditions in a group of limited community ambulatory (gait velocity between 58 and 80cm/s) and full community ambulatory subjects (minimum gait velocity, 80cm/s) with chronic stroke.
Notes	Control group had no intervention so groups not treated equally. Coordination aim confirmed by outcome measures. lack of follow-up. effects were measured in both single and dual task walking. GaitRite measures but only single limb support time as only relevant

Risk of bias

Item	Author's judgement	description
Allocation concealment	unclear	Computer generated random order. randomization list was overseen by one of the investigators who had no contact with participants until group assignment was revealed.
Blinding of outcome assessors	unclear	Further, group assignment was not revealed to study personnel until the participant was consented and baseline testing was complete
baseline characteristics equal	Yes	
Intention to treat analysis	Yes	No drop outs

Appendix V: Characteristics of Excluded Studies

Citation	Comments	Citation	Comments
Aruin et al, 2000	effect on insole insert and goal directed balance exercise, not locomotor practice	Daly et al, 2007	effect of IM-FNS on gait coord
Bacik et al, 2006	no intervention, no control comparison (except to healthy counterparts) & measures pooled between limbs	Daly et al, 2007	describes how evidence can be used to design efficacious interventions for coord
Balasubramaniam et al, 2007	explores relationship between spatial symmetry and other walking parameters but doesn't evaluate an intervention	Daly et al, 1993	case study of feasibility of FNS system - insufficient measures (not bi-lateral)
Bayat et al, 2005	contrasts symmetry improvements made from overground walking vs treadmill training in acute patients only	de Bujanda, 2004	describes asymmetry and coordination at different gait speeds for stroke vs healthy, no intervention
Bogatag et al, 1989	reports temporal symmetry following FES but means pooled for both limbs	de Seze et ak, 2001	RCT of bobath and trunk posture training device but no coord measures
Bowden et al, 2006	explores relationship between GRFs with other gait params/severity but not intervention	den Otter, 2005	describes stepping coordination for crossing obstacles under different time constraints - no intervention, and no data for control trials with gait and no obstacle
Chen et al, 2001	describes forces used in cane assisted walking, no intervention	den Otter, 2006	describes EMG recovery over time during current practice PT, no aim to intervene on coordination
Chen et al, 2005	describes diffs in gait params between healthy and hemiparetic, no intervention	Duetsch et al, 2007	virtural reality to enable walking, more feasibility than examination of intervention
Colborne et al, 1993	not locomotor practice intervention, looks at bio-feedback regarding ankle control and RoM	Dickstein et al, 2004	case report of effect of imagery on gait coordination in acute participant only
Combs et al, 2007	effect of BWSTT + strength training on functional gait outcomes, insufficient coordination measures	Dion et al, 2003	assessing validity of measuring gait with rise to walk task - no intervention

Cordo et al, 2009	effect of AMES (ankle joint stimulator) on some gait params but symmetry is presented as combined means for both legs	Dunsky et al, 2008	effects of imagery on gait coord & params in acute patients
Cozean et al,1988	pseudo-random CT of Bio-FB and FES on gait, stride length pooled between legs	Eich et al, 2004	rct of bobath vs tt on gait - no kinematic coord msrs
Cross et al, 2003	effect of slider shoe - not locomotor practice- ABA design for 4 stroke subjects, only speed outcome measure	El-Abd et al, 1994	cortical activation during gait - no intervention, no gait measures
Cruz et al, 2008	describes isometric hip torque production for stroke participants, but no intervention, no gait measures	Engardt et al, 1995	assess eccentric vs concentric strength training on function - only presents % swing time of paretic leg
Daly et al, 2006	effect of intramuscular FNS on gait coord - but coord measures are pooled for both limbs	Ford et al, 2007	phase manipulation and walking in stroke
Garcia et al, 2001	gait coordination during stepping in place compared to healthy, descriptive of deficits not an intervention	Hesse et al, 1999	overground vs bwstt on gait params, but reports on ability to use bwstt not aiming to intervene on coordination
Garrett et al, 2001	describe changes in reflex activity during walking in stroke vs healthy, no intervention	Hesse et al, 2001	explains the building of a mechanised gait trainer, no intervention
Gelber et al, 1995	bobath vs. task specific - no aim to intervene on coordination and coord measures (stride length pooled over both legs)	Hidler et al, 2009	RCT of BWSTT vs current practice but no kinematic measures for each leg
Gladstone et al, 2006	double blind placebo RCT of PT vs PT+drug - no kinematic measures of coord	Hodt-billington et al, 2008	to see if trunk measures can identify asymmetrical gait - no intervention
Gok et al, 2003	effects of 2 different afo's on stroke gait - gait params pooled between limbs	Hsu et al, 2003	relationship between impairments and gait params and determinants of velocity and asymmetry
Hajek et al, 1993	effect of visuospatial training on locomotor outcomes - no coord aims or measures	Huitema et al, 2004	effect of isokinetic/isotonic stretch on gait performance- gait measures not presented for both legs

Harris-love et al, 2004	overground vs. treadmill walking on EMG - no kinematic coord measures	Huseman et al, 2007	pilot intervention lokomat trainer vs. current practice for acute patients only
Hase et al, 2008	prosthetic/walking aide on paretic limb function, not locomotor practice intervention	Intiso et al, 1994	stride length and stride times pooled for both limbs
Hart et al, 2004	Tai-Chi practice, no coordination aim or measures	Isakov et al, 2002	FES on paretic leg function not on gait coordination
Hausdorff et al, 2008	prosthesis on walking function, not locomotor practice intervention	Jaffe et al, 2004	no aim to address coordination, only step length presented
Hesse et al, 2000	feasibility of using mechanised gait trainer only EMG measures reported	Jones et al, 1999	effect of serial casts on acute patients
Hesse et al, 1997	ABA design to assess BWS but no kinematic measures reported for each leg	Jones et al, 1999	duplicate of previous Jones - this is erratum and case in point discussion
Hesse et al, 1995	effect of botox vs FNS+botox on EMG and spasticity	Kilbreathe et al, 2006	effect of gluteal tapping on gait params not locomotor practice
Hesse et al, 1999	compared gait measures between stepping machine and treadmill training-measures of EMG	Kim et al, 2003	relationship between symmetry of GRF and spatio-temporal gait params, no intervention
Hesse et al, 1999	effect of AFO on gait params not locomotor practice	Kim et al, 2003	relationship between isometric torque and gait function, no intervention
Klimstra et al, 2009	NOT STROKE effect of arm swing on gait params but no kinematic gait coord msrs just PCA and correlations	Malezic et al, 1994	restoration of standing with FES, not locomotor practice or gait coordination aim
Kluding et al, 2008	pilot test assessing functional practice vs ankle ROM+functional practice - no coord measures	Malouin et al, 1993	timing and intensity of task specific therapy but no aim to address coord an no measures
Kottink et al, 2008	rct of FES vs no therapy - no coord msrs	Maynard et al, 2005	effect of isokinetic/isotonic stretch on gait performance- gait measures not presented for both legs or symmetry index
Krishnamoorthy et al, 2008	prosthesis on gait, not locomotor practice	Mccain et al, 2008	effect of BWSTT before overground practice on gait outcomes in acute patients

Kuan et al, 199	effect of using a cane, no aim to specifically address coord just explore effects	McCain et al, 2007	BWSTT vs OG in acute patient, no coordination aim
Kwakkel et al, 2002	effect of duration of intervention, speed of walking practice on gait outcomes - no kinematic coord msrs	Merholz et al, 2007	predictive validity and responsiveness to change in FAC following 4-6 weeks current practice intervention - no kinematic coord measures
Lamontagne et al, 2007	effect of stroke on turning coordination, compares to healthy participant, no control condition to contrast within stroke participants and descriptive aim not intervention	mirelman et al, 2009	transferability of effect of VR gait training to overground walking performance- step length not provided for both limbs so insuff coord msrs
Lamontagne et al, 2004	ability of stroke patients to alter speed, not effect of speed on coordination	Montoya et al, 1994	no bilateral gait measures or symmetry
Lamontagne et al, 2005	effect of head turning on gait coordination compared to healthy - descriptive study of stroke related deficits not an intervention aimed at remediating coordination	Neckel et al, 2008	effect of gait training on symmetry of kinematics but comparisons to controls no ABA design
Laufer et al, 2001	TT vs OG in acute patients only	Olney et al, 1993	computer assisted FB, preliminary report no measures presented
Lehmann et al, 2007	AFO not locomotor practice	Partridge et al, 2000	effect of dose of Bobath, no coordination aim or measures
Lin et al, 2005	determine relationship between joint position sense and gait function, no intervention	Patterson et al, 2008	relationship between symmetry and SSWS
Lin et al, 2006	relationship between ankle impairments and gait function	Perell et al, 2000	only pedal force data presented - not locomotor practice and no coord measures or aim
Lord et al, 2006	effect of dual task and environment on gait params - coord msrs insufficient	Peurala et al, 2009	intentsity of gait trainer and effects on floor walking, no coordination measures
Lu et al, 1997	effect of cane length on stability, not locomotor practice and no aim to intervene on coordination	Pohl et al, 2001	comaprison of different TT on gait - no separate coord measures for paretic and non paretic sides

Pohl et al, 2002	RCT of different forms of gait training - stride length is mean of both legs	Tenore et al, 2006	reliability of gait analysis in directing rehab
Prassas et al, 2007	effect of aud cue on walking but used acute and chronic participants	Thaut et al, 1997	effect of aud cue on gait training for acute patients only
Puh et al, 2009	no intention to treat coordination - just comparison of TT and OG	Thaut et al, 2007	RAS vs bobath for acute patients only
Regenaux et al, 2008	effect of different TT on walking used HEALTHY subject	Thaut et al, 1993	auditory cueing on gait - acute patients
Richards et al, 2004	task oriented training and strenght training vs walking over ground- no aim to address coordination, no coord measures	Titianova et al, 1995	predictive ability of footprint measures on recovery capacity
Ring et al, 2009	effect of afo vs neuroprosthesis on gait but stroke data combined with TBI data	Trueblood et al, 1989	effect of pelvic motion resistance intervention on gait not locomotor practice
Roth et al, 1997	relationship between speed an other temporal gait params	Turns et al, 2007	relationship of EMG and GRF in stroke gait
Rydwik et al, 2006	effect of stretching intervention on walking ability- no coord aim or msrs	Tyson et al, 1999	effect of different walking aides on trunk movements during gait- not locomotor practice
Said, 2005	no ABA comparison of stroke before and after obstacle crossing as in an intervention	Tyson et al, 2001	effect of hinged AFO on gait - not locomotor practice
Said, 1999	no ABA comparison of stroke before and after obstacle crossing as in an intervention	Tyson et al, 1998	hinged afo single case study - not locomotor practice
Schauer et al, 2003	effect of additional aud feedback on gait training in acute patients only	Wagenaar et al, 1992	kinematic analysis using speed as a basis, no intervention
Shiavi et al, 1979	EMG data only	Wall et al, 1987	home exercise in management of gait asymmetry, measures not presented bilaterally
Sibley et al, 2008	effect of fatigue on gait - with ABA comparison within stroke group	Wang et al, 2007	AFO not locomotor practice

Silver et al, 2000	effect of aerobic TT on gait, not locomotor practice intervention is exercise	Werner et al, 2002	RCT of BWS + current practice vs. current practice alone but no coord measures
Stephens et al, 1999	effect of floor surface on gait but no coordination aims or measures	Werner et al, 2007	effect of incline on TT on gait with acute patients only
Wong et al, 2004	feasibility of using foot contact pattern to predict severity		
Xue et al, 2006	early motor relearning program no aim to improve coordination		
Yan et al, 2005	FES in acute patients		
Yang et al, 2005	effect of backward walking insufficient coordination measures		
Yang et al, 2006	effect of functional strength training on gait- gait measures not presented bilaterally		
Yavuzer et al, 2006	effect of biofeedback on force plate during standing on gait function- not locomotor practice		
Yavuzer et al, 2006	rct of FES on gait- gives % swing for P limb but not both		
Yelnick et al, 2008	rct of bobath vs. multisensorial training- insufficient coordination measures		
Yen et al, 2008	effect of BWST on cortico-motor excitability no gait coordination measures		
You et al, 2005	virtual reality induced cortical reorganization, no gait coordination measures		

Appendix VI: Fugl-Meyer Lower Extremity Assessment (Fugl-Meyer et al. 1975)

Item		Task	Scoring Criteria	Score
Reflex Activity	Patellar	Supine	0: no reflex 2: reflex exists	
	Achilles			
Flexor-Synergy	Hip	Supine. *flex hip, knee and ankle maximally.* Abduct hip and rotate outwards	0: can't do 1: part range 2: full range	
	Knee			
	Ankle			
Extensor Synergy	Hip	Supine. *extend hip, knee and ankle joints.* Resist extension & adduct hip	0: can't do 1: part resistance 2:large resistance	
	Knee			
	Ankle			
Deviate from Synergy	Knee flexion	Sitting knees free of bed. *Flex knee beyond 90°*	0:can't do 1: <90° 2: >90°	
	Ankle dorsi-flexion	Sitting knees free of bed. *Dorsi flex ankle*	0: can't do 1: part range 2: full range	
Little synergy	Knee flex	Standing. *Flex knee to at least 90° , hip at 0°*	0:can't do 1: <90° 2: >90°	
	Ankle dorsi	Standing. *Dorsi-flex ankle*	0: can't do 1: part range 2: full range	
Normal Reflex		Supine	0: 2 hyper 1: 1 hyper 2: normal	
Coordination/Speed	Tremor/ Dysmetria	Supine. *Bring heel to knee cap of opposite leg 5 times as quickly as possible*		
	Time	Non-affected: sec Affected: sec	0: ≥6 sec slower 1: 2~5 sec slower 2: < 2 sec slower	
			Total:	**/34**

Appendix VII: Berg Balance Scale (Berg 1989)

Item No.	Item description		Score
1	***Sitting to standing*** *Please stand up. Try not to use your hands for support.*	4 able to stand without using hands and stabilize independently 3 able to stand independently using hands 2 able to stand using hands after several tries 1 needs minimal aid to stand or to stabilize 0 needs moderate or maximal assist to stand	
2	***Standing unsupported*** *Please stand for two minutes without holding.*	4 able to stand safely 2 minutes 3 able to stand 2 minutes with supervision 2 able to stand 30 seconds unsupported 1 needs several tries to stand 30 seconds unsupported 0 unable to stand 30 seconds unassisted	
3	***Sitting unsupported*** *Please sit with arms folded for 2 minutes.*	4 able to sit safely and securely 2 minutes 3 able to sit 2 minutes under supervision 2 able to sit 30 seconds 1 able to sit 10 seconds 0 unable to sit without support 10 seconds	
4	***Standing to sitting*** *Please sit down.*	4 sits safely with minimal use of hands 3 controls descent by using hands 2 uses back of legs against chair to control descen 1 sits independently but has uncontrolled descent 0 needs assistance to sit	
5	***Transfers***	4 able to transfer safely with minor use of hands 3 able to transfer safely definite need of hands 2 able to transfer with verbal cueing and/or supervision 1 needs one person to assist 0 needs two people to assist or supervise to be safe	
6	***Standing with eyes closed*** *Please close your eyes and stand still for 10 seconds.*	4 able to stand 10 seconds safely 3 able to stand 10 seconds with supervision 2 able to stand 3 seconds 1 unable to keep eyes closed 3 seconds but stays steady 0 needs help to keep from falling	
7	***Standing with feet together*** *Place your feet together and stand without holding.*	4 able to place feet together independently and stand 1 minute safely 3 able to place feet together independently and stand for 1 minute with supervision 2 able to place feet together independently but unable to hold for 30 seconds 1 needs help to attain position but able to stand 15 seconds feet together 0 needs help to attain position and unable to hold for 15 seconds	

8	**Reaching forward with outstretched arm** *Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can.* *(When possible, ask subject to use both arms when reaching to avoid rotation of the trunk.)*	4 can reach forward confidently >25 cm 3 can reach forward >12 cm safely 2 can reach forward >5 cm safely 1 reaches forward but needs supervision 0 loses balance while trying/requires external support	
9	***Retrieving object from floor*** *Pick up the shoe/slipper which is placed in front of your feet.*	4 able to pick up slipper safely and easily 3 able to pick up slipper but needs supervision 2 unable to pick up but reaches 2-5cm from slipper and keeps balance independently 1 unable to pick up and needs supervision while trying 0 unable to try/needs assist to keep from losing balance or falling	
10	***Turning to look behind*** *Turn to look directly behind you over toward left shoulder. Repeat to the right.*	4 looks behind from both sides and weight shifts well 3 looks behind one side only other side shows less weight shift 2 turns sideways only but maintains balance 1 needs supervision when turning 0 needs assist to keep from losing balance or falling	
11	***Turning 360°*** *Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.*	4 able to turn 360 degrees safely in 4 seconds or less 3 able to turn 360 degrees safely one side only in 4 seconds or less 2 able to turn 360 degrees safely but slowly 1 needs close supervision or verbal cueing 0 needs assistance while turning	
12	***Placing alternate foot on stool*** *Place each foot alternately on the step/stool. Continue until each foot has touched the step/stool four times.*	4 able to stand independently and safely and complete 8 steps in 20 seconds 3 able to stand independently and complete 8 steps >20 seconds 2 able to complete 4 steps without aid with supervision 1 able to complete >2 steps needs minimal assist 0 needs assistance to keep from falling/unable to try	
13	***Standing with one foot in front*** *Place one foot directly in front of the other. If you feel that you cannot place your foot directly in front, try to step far enough ahead that the heel of your forward foot is ahead of the toes of the other foot.*	4 able to place foot tandem independently and hold 30 seconds 3 able to place foot ahead of other independently and hold 30 seconds 2 able to take small step independently and hold 30 seconds 1 needs help to step but can hold 15 seconds 0 loses balance while stepping or standing	
14	***Standing on one foot*** *Stand on one leg as long as you can*	4 able to lift leg independently and hold >10 seconds 3 able to lift leg independently and hold 5-10 seconds 2 able to lift leg independently and hold = or >3 seconds 1 tries to lift leg unable to hold 3 seconds but remains	

	without holding.	standing independently 0 unable to try or needs assist to prevent fall	
	Total	Exclusion BBS score < 45	**/ 56**

Appendix VIII: Falls Events Questionnaire (Stack 1999)

Have you fallen in the past year?
What was the location of the fall?
What activity were you doing when you fell?
What do you think caused the fall?
Do you recall the approximate time of the fall?
How did you land?
Did you injure yourself when you fell?
Do you feel fearful of falling?

Appendix IX: Bespoke Matlab script written by the author to identify axial segment onset latencies

```
%THIS SCRIPT FINDS THE ONSET OF SEGMENT REORIENTATION BY DETERMINING WHEN
%AN INDIVIDUAL TURN TRIAL GOES OUTSIDE OF THE 3SD BOUNDARY FROM THE 10
%STRAIGHT TRIALS AND THEN LOOKS BACK FROM THAT POINT IN TIME TO FIND THE
%FIRST ZERO CROSSING IN JERK AND CALLS THIS POINT THE POINT OF ONSET
%   FOR THIS SCRIPT TO WORK
%       1)trigger_mat, open_files and derivative scripts must already have
%       been run in that order

%First select the Velocity variable structure for onset latency detection and establish the disp variable structure
name
clear onset
vel_var=input('Please input the VEL variable structure name: ','s');
    LLvel_data_loc=[vel_var '.L_Late_Data'];
    LEvel_data_loc=[vel_var '.L_Early_Data'];
    RLvel_data_loc=[vel_var '.R_Late_Data'];
    REvel_data_loc=[vel_var '.R_Early_Data'];
disp_var=vel_var(1:strfind(vel_var,'_JERK')-1);
    LEdisp_data_loc=[disp_var '.L_Early_data'];
    LLdisp_data_loc=[disp_var '.L_Late_data'];
    REdisp_data_loc=[disp_var '.R_Early_data'];
    RLdisp_data_loc=[disp_var '.R_Late_data'];
    SLLdisp_data_loc=[disp_var '.ST_L_Late_data'];
      SLEdisp_data_loc=[disp_var '.ST_L_Early_data'];
      SRLdisp_data_loc=[disp_var '.ST_R_Late_data'];
      SREdisp_data_loc=[disp_var '.ST_R_Early_data'];

%Then pool the straight trials displacement data with the same lead leg from across cue conditions to get a 10
trial 3SD boundary
 SDbounds.St_L_data=eval([SLEdisp_data_loc '(:,1:5)']);
 SDbounds.St_L_data(1:7200,6:10)=eval([SLLdisp_data_loc '(:,1:5)']);
 SDbounds.St_R_data=eval([SREdisp_data_loc '(:,1:5)']);
 SDbounds.St_R_data(1:7200,6:10)=eval([SRLdisp_data_loc '(:,1:5)']);

 %filter the straight data imported above
% [b,a]=butter(2,6/60,'low');
 %SDbounds.St_L_data=filtfilt(b,a,SDbounds.St_L_data);
 %SDbounds.St_R_data=filtfilt(b,a,SDbounds.St_R_data);

 %now calculate the mean and SD boundaries of the straight data.
for j=1:7200
   SDbounds.St_L_data(j,11)=mean(SDbounds.St_L_data(j,1:10));              %SHOULD INDEX THE
COLUMN NUMBER THAT THE MEAN IS TAKEN OVER & LOOK FOR THE NUMBER OF COLUMNS
OF NON-ZERO DATA(LOOK AT FRAME 3600 TO BE NON ZERO),TO ACCOMODATE SUBJECTS
WHO DON'T HAVE ALL 10 ST TRIALS
   SDbounds.St_L_data(j,12)=SDbounds.St_L_data(j,11)+3*(std(SDbounds.St_L_data(j,1:10)));
   SDbounds.St_L_data(j,13)=SDbounds.St_L_data(j,11)-3*(std(SDbounds.St_L_data(j,1:10)));
end
for j=1:7200
   SDbounds.St_R_data(j,11)=mean(SDbounds.St_R_data(j,1:10));
   SDbounds.St_R_data(j,12)=SDbounds.St_R_data(j,11)+3*(std(SDbounds.St_R_data(j,1:10)));
   SDbounds.St_R_data(j,13)=SDbounds.St_R_data(j,11)-3*(std(SDbounds.St_R_data(j,1:10)));
end

%find the onset latency for each trial
```

```
numfiles = size(eval([disp_var '.L_Late_Names']),2);                    %look to see how many trials there are for the turns by looking at the number of trial names in the name section of the structure

for i=1:numfiles

   AllSDout=find(eval([LLdisp_data_loc '(:,i)'])<SDbounds.St_L_data(:,13));
   SDout_length=length(AllSDout);

   for r=1:SDout_length;
    if AllSDout(r+120,1)-AllSDout(r,1)==120;
      SDout=AllSDout(r);
      break;
    else;
      continue;
    end;
   end;

 X=0;
 while X==0
    if 0<eval([LLvel_data_loc '(SDout-1,i)'])&& eval([LLvel_data_loc '(SDout,i)'])<0   %then look to the velocity data starting at the frame where the disp went outside the SD boundary and look for the first zero crossing PREceeding the SDbound out
       onset.L_L_data(1,i)=(SDout(1,:)-3599)/120;                    %convert onset frame to time with respect to trigger mat frame;all trigger mat frames are on row 3599 so subtract 3599 from onset frame obtained above and convert to seconds for sampling freq of 120Hz
        X=1;
    else
      SDout=SDout-1;
    end
 end

end
```

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